



Proceedings

ASPE 2014 Spring Topical Meeting

Dimensional Accuracy and Surface Finish in Additive Manufacturing

April 13-16, 2014

American Society for

Precision Engineering

P.O. Box 10826, Raleigh, NC 27605-0826
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Preface

This book comprises the proceedings of the ASPE 2014 Spring Topical Meeting entitled **Dimensional Accuracy and Surface Finish in Additive Manufacturing**. The contributions reflect the authors' opinions and are published as presented to ASPE without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE or its editorial staff.

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in

Additive Manufacturing

ASPE Spring Topical Meeting

April 13-16, 2014

University of California - Berkeley
Berkeley, California, USA

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

Founded in 1986, ASPE provides a new focus for a diverse but important community. Other professional organizations have covered aspects of precision engineering, always as a sideline to their principal goals. ASPE is based on the core of generic concepts necessary to achieve precision in any application; independent of discipline, ASPE intends to be the focus for precision technology, and to represent all facets from research to application.

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Table of Contents

Preface	ii
Contents	iii
Schedule	iv
Foreword	v
Sustaining Corporate Sponsors	vi
Corporate Sponsors	vii
Technical Paper Index	viii-xiii
Technical Papers	3-224
Author Index	225-226

Meeting Schedule

	Sun., April 13 Hotel Shattuck		Mon., April 14 UC-Berkeley Bechtel Building Sibley Auditorium		Tues., April 15 UC-Berkeley Bechtel Building Sibley Auditorium		Wed., April 16 UC-Berkeley Bechtel Building Sibley Auditorium
7:00	Registration and Continental Breakfast						
		7:30	Registration and Continental Breakfast	7:30	Registration and Continental Breakfast	7:30	Registration and Continental Breakfast
8:00	TUTORIAL I Crystal Ballroom II TUTORIAL II Crystal Ballroom I	8:15	WELCOME REMARKS & SESSION I PLENARY	8:15	OPENING REMARKS & SESSION III DESIGN AND OPTIMIZATION	8:15	OPENING REMARKS & SESSION VI METROLOGY CHALLENGES
10:00	Coffee Break	10:00	Coffee Break	10:00	Coffee Break	10:00	Coffee Break
10:30	TUTORIAL I & II CONTINUED	10:30	SESSION II PLENARY	10:30	SESSION IV MODELING & MICROSTRUCTURE	10:30	SESSION VII VALIDATION OF AM PROCESSES AND TOOLS
11:30	Boxed Lunch						
12:30	TUTORIAL I CONTINUED	12:00	Lunch On-Your-Own	12:00	Lunch On-Your-Own	12:30	Lunch On-Your-Own
1:30	Coffee Break	1:30		1:30			
1:45	TUTORIAL I CONTINUED		COMMERCIAL SESSION		SESSION V NEW DEVELOPMENTS IN AM TOOLS AND HYBRID PROCESSES	2:00	SESSION VIII ACHIEVING TIGHT TOLERANCES
		3:00	Coffee Break				
3:15	Coffee Break						
3:30	TUTORIAL I CONTINUED	3:30	COMMERCIAL AND TECHNICAL POSTERS Garbarini Lounge	3:30	Coffee Break	3:45	Coffee Break
				3:45	COMMERCIAL AND TECHNICAL POSTERS Garbarini Lounge	4:00	SESSION IX METROLOGY OF SURFACES
5:00		5:00	BUS TO HOTEL/ PYRAMID ALEHOUSE*	5:15		5:30	END CONFERENCE
		6:00					
6:30	WELCOME RECEPTION CRYSTAL BALLROOM					6:00	
8:00			PYRAMID ALEHOUSE DINNER				After-Meeting Gathering The Faculty Club
		9:00					

*Bus will make brief stop at near-by hotels to drop-ff personal belongings before going dinner.

Foreword

This meeting of the American Society for Precision Engineering on **Dimensional Accuracy and Surface Finish in Additive Manufacturing** will focus on 1) Dimensional Accuracy and Surface Finish from Additive Manufacturing (AM): what dimensional control is needed for AM for precision applications; State-of-the-Art – what is achievable today and what developments are underway; issues and timeline for meeting precision tolerances (Gap analysis). 2) Design for manufacturing: design rules for additive manufacturing and impact of dimensional errors on structures designed using optimization methodologies. 3) Standards: certifying AM equipment capabilities and artifacts for assessing machine performance – Round-robin testing. 4) Using AM-Fabricated components in precision assemblies: component-to-component relationships, stack-up tolerances, friction, robotic grip-ability. 5) Combining AM with secondary finishing operations 6) Metrology: external surfaces and internal features; in-situ instrumentation; materials validation and 7) Mechatronics and controls for achieving dimensional tolerances.

We encourage presentations of a tutorial nature which elaborate principles essential to achieving high performance. We aim to bring together specialists and practitioners from industry, government, and academia for the exchange of ideas and to identify topics for further research. The conference schedule will include significant unstructured time to allow for technical and social interactions.

2014 Spring Topical Meeting Program Committee

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Technical Sessions

Session I

Plenary

Monday, April 14, 2014, 8:15 AM - 10:00 AM

Session Chairs: John S. Taylor, Lawrence Livermore National Laboratory and
Eckart Uhlmann, Fraunhofer Institute for Production Systems and Design, Berlin

- 1. Welcome and Opening Remarks**
Taylor, J. S. (Lawrence Livermore National Laboratory)
- 2. GE Aviation Perspective on Precision Capabilities of Additive Manufacturing**
Rengers, S. (GE Aviation) 3
- 3. Metrology Needs for Additive Manufacturing**
Kurfess, T. R. (Georgia Institute of Technology); Taylor, J. S. (Lawrence
Livermore National Laboratory) 4
- 4. Modeling and Simulation of Additive Manufacturing Processes**
King, W. E.; Anderson, A. T.; Ferencz, R. M.; Hodge, N. E.; Kamath, C.;
Khairallah, S. A. (Lawrence Livermore National Laboratory) 7

Session II

Plenary

Monday, April 14, 2014, 10:30 AM - 12:00 PM

Session Chairs: David A. Dornfeld, University of California - Berkeley and
Vivek G. Badami, Zygo Corporation

- 1. Topology Optimization and Additive Manufacturing, Natural Counterparts
for Precision Systems - State-of-the-Art and Challenges**
van Keulen, F.; Langelaar, M. (Delft University of Technology);
van Baars, G. (TNO Technical Sciences) 9
- 2. An Engineered Approach for Combined Additive and Subtractive Manufacturing***
Lell, F. (DMG-Mori Seiki, Sauer GmbH)
- 3. Metals-Based Additive Manufacturing: Metrology Needs and Standardization Efforts**
Slotwinski, J. A.; Moylan, S. P. (National Institute of Standards and Technology) 11

Commercial Session

Monday, April 14, 2014, 1:30 PM - 3:00 PM

Session Chairs: Pete J. Fitsos, Lawrence Livermore National Laboratory and
Alexander H. Slocum, Massachusetts Institute of Technology

**No abstract provided at this time*

Session III

Design and Optimization

Tuesday, April 15, 2014, 8:15 AM - 10:00 AM

Session Chairs: Andre A. Claudet, Sandia National Laboratories and
Thomas A. Dow, North Carolina State University

1. Opening Remarks

Taylor, J. S. (Lawrence Livermore National Laboratory)

2. Optimization of Media Feed Channels in Laser Beam Melting

Reinarz, B.; Sehr, J. T.; Gerd, W. (Universität Duisburg-Essen); Deiss, O.;
van Kampen, J.; Mönzer, J.; Ott, M. (Siemens AG) 13

3. Verification of Design Rules for Additive Manufacturing

Uhlmann, E.; Bergmann, A.; John, P.; Kashevko, V. (Fraunhofer-Institute
Production Systems and Design Technology (IPK)) 19

4. AM Design of a Wafer Conditioning Table

Oosterhuis, G.; Villegas, A.; Ciftci, M.; Vogels, J.; Schutten, G. J.;
Riahi, G. (VDL Enabling Technologies Group) 24

**5. Extension of Prior Developed Design Rules' Range of Validity for Different
Boundary Conditions in Laser Sintering**

Adam, G. A. O.; Zimmer, D.; Müller, M. (University of Paderborn) 30

Session IV

Modeling and Microstructure

Tuesday, April 15, 2014, 10:30 AM - 12:00 PM

Session Chairs: Richard K. Leach, National Physical Laboratory, UK and
Wayne King, Lawrence Livermore National Laboratory

**1. Evaluation of the Effect of Defects on the Mechanical Performance of
Components Manufactured by Selective Laser Melting**

Leuders, S.; Tröster, T.; Brenne, F.; Riemer, A.; Richard, H. A.;
Niendorf, T. (University of Paderborn) 36

**2. Predictive Modeling Capabilities for Dimensional Accuracy and Surface Finish
in Metal Laser Melting Based Additive Manufacturing**

Patil, N.; Pal, D.; Anam, M.; Gong, H.; Gu, H.; Dilip, S.;
Stucker, B. (University of Louisville) 37

**3. Estimation of Surface Roughness of Additive Manufacturing Parts
Using Finite Difference Method**

Barari, A.; Jamiolahmadi, S. (University of Ontario Institute of Technology) 43

**4. The Influence of Heat Accumulation on the Surface Roughness in
Additive Manufacturing by Electron Beam Melting (EBM)®**

Jamshidinia, M.; Kovacevic, R. (Southern Methodist University) 45

Session V

New Developments in AM Tools and Hybrid Processes

Tuesday, April 15, 2014, 1:30 PM - 3:30 PM

Session Chairs: Alexander H. Slocum, Massachusetts Institute of Technology and
Stephen J. Ludwick, Aerotech, Inc.

- 1. Typical Requirements for Precision Mechanical Parts and Opportunities for Additive Manufacturing**
Goudsmit, F.-W.; Oosterhuis, G.; Sluiter, E.; Peijnenburg, A. T. (VDL Enabling Technologies Group) 51
- 2. Maximising Dimensional Accuracy from Additive Laser Melting Builds**
Jones, N. H. (Renishaw, plc). 56
- 3. Finishing of Electron Beam Melted Titanium (Ti6Al4V) Using Shape Adaptive Grinding Tools**
Beaucamp, A. T.; Namba, Y. Y. (Chubu University); Charlton, P.; Graziano, A. (Zeeko). 62
- 4. Hybrid Manufacturing of Complex Molds and Dies Using Additive Metals and CNC**
Murray, J. D. (Concept Laser GmbH) 66
- 5. A Solution for Indexing 3D Printed Parts onto Secondary Machining Platforms**
Pawlikowski, G. T. (TE Connectivity). 67

Session VI

Metrology Challenges

Wednesday, April 16, 2014, 8:15 AM - 10:00 AM

Session Chairs: Vivek G. Badami, Zygo Corporation and
Hy D. Tran, Sandia National Laboratories

- 1. Opening Remarks**
Taylor, J. S. (Lawrence Livermore National Laboratory)
- 2. History and Development of Process Control for Additive Manufacturing**
Beaman, J. J.; Fish, S.; Bourell, D. L. (University of Texas at Austin);
Leigh, D. K. (Harvest Technologies) 70
- 3. CT to Evaluate of Distortions in Stainless-Steel AM Structures**
Martz Jr., H. E.; Divin, C. J.; Panas, R. M.; Brown, W. D.; Burke, S.; Rathbun, H.;
Alexander, P. A.; Smith, J. A.; Taylor, J. S. (Lawrence Livermore National Laboratory). 71
- 4. Dimensional Accuracy of Internal Channels in SLM Produced Parts**
Kempen, K.; Welkenhuyzen, F.; Qian, J.; Kruth, J.-P. (University
of Leuven (KU Leuven)) 76
- 5. Qualifying Manufacturing Variability Using Analytical Computed Tomography of Direct Metal Laser Sintered Test Structures**
Saint John, D. B.; Jones, G.; Reutzel, E.; Coward, A.; Joshi, S.; Thole, K.;
Simpson, T. (The Pennsylvania State University) 80

Session VII

Validation of AM Processes and Tools

Wednesday, April 16, 2014, 10:30 AM - 12:30 PM

Session Chairs: Gregory T. Pawlikowski, TE Connectivity and
Sanjay B. Joshi, Pennsylvania State University

- 1. Assessment of Guidelines for Conducting Round Robin Studies in Additive Manufacturing**
Moylan, S. P.; Slotwinski, J. A. (National Institute of Standards and Technology) 82
- 2. Study of Accuracy of Parts Produced Using Additive Manufacturing**
Bauza, M. B.; Knebel, R.; Bhogaraju, R.; O'Connell, M. T.; Smokovitz, J. D. (Carl Zeiss Industrial Metrology); Moylan, S. P. (National Institute of Standards and Technology); Panas, R. M.; Burke, S.; Martz Jr., H. E.; Taylor, J. S.; Alexander, P. (Lawrence Livermore National Laboratory) 86
- 3. Proficiency Testing for Interlaboratory Comparisons on Industrial Computed Tomography**
Villarraga, H.; Hocken, R. J.; Morse, E. P.; Smith, S. T. (University of North Carolina at Charlotte) 92
- 4. Understanding Error Generation in Fused Deposition Modeling**
Bayley, C.; Hurlbut, C.; Helu, M.; Dornfeld D. A. (University of California at Berkeley); Bochmann, L.; Transchel, R. (Swiss Federal Institute of Technology) 98
- 5. Performance Verification of 3D Printers**
Hansen, H. N.; Nielsen, J. S.; Rasmussen, J.; Pedersen, D. B. (Technical University of Denmark). 104

Session VIII

Achieving Tight Tolerances

Wednesday, April 16, 2014, 2:00 PM - 3:45 PM

Session Chairs: Allister James, Siemens Energy, Inc. and
John S. Taylor (Lawrence Livermore National Laboratory)

- 1. Understanding Modern Direct Metal Laser Melting and Achieving Tight Tolerances**
Rengers, S. (GE Aviation) 108
- 2. On-line Quality Measurements in Laser Powder Bed Fusion**
Clijsters, S.; Craeghs, T.; Buls, S.; Kruth, J.-P. (University of Leuven (KU Leuven)); Bechmann, F.; Ebert, M. C. (Concept Laser GmbH) 109
- 3. A Hybrid Manufacturing Process for Precision Metal Parts**
Liou, F.; Sparks, T. E.; Liu, H. (Missouri University of Science and Technology). 114
- 4. Improving Dimensional Accuracy and Surface Finish on Freeform Components Using Commercially-Available Machine Tools**
Roblee, J. W. (AMETEK - Precitech, Inc.) 119
- 5. Powder Bed Fusion Machine Performance Testing**
Moylan, S. P.; Donmez, M. A. (National Institute of Standards and Technology); Drescher, J. D. (UTC - Pratt & Whitney) 123

Session IX

Metrology of Surfaces

Wednesday, April 16, 2014, 4:00 PM - 5:30 PM

Session Chairs: Shawn P. Moylan, National Institute of Standards and Technology and Richard K. Leach, National Physical Laboratory, UK

- 1. Surface Texture Measurement for Additive Manufacture**
Triantaphyllou, A.; Milne, K. (The Manufacturing Technology Centre); Giusca, C.; Macaulay, G.; Leach, R. K. (National Physical Laboratory) 127
- 2. Metrology for Additive Manufacturing Parts and Processes**
Jared, B. H.; Tran, H. D.; Saiz, D. (Sandia National Laboratories); Boucher, C.; Dinardo, J. (Honeywell Federal Manufacturing & Technologies) 131
- 3. Characterizing Additive Manufacturing Parts Using Coherence Scanning Interferometry**
Fay, M. F.; Badami, V. G.; Colonna de Lega, X. (Zygo Corporation) 135
- 4. Characterization of Additive Manufactured Surfaces with Confocal Microscopy**
Grimm, T.; Witt, G. (University of Duisburg-Essen); Wiora, G. (NanoFocus AG) 139

Poster Sessions

Technical and Commercial Poster Session

Monday, April 14, 2014, 3:30 PM - 5:00 PM

Tuesday, April 15, 2014, 3:45 PM - 5:15 PM

Session Chairs: Thomas A. Dow, North Carolina State University and Senajith B. Rekawa, Lawrence Berkeley National Laboratory

AM Error Analysis

- 1. Effect of Direct Slicing on Geometric Tolerances in Additive Manufacturing Process**
Barari, A. (University of Ontario Institute of Technology) 145
- 2. Design of Dynamic Focusing Unit for 3D Laser Scanner**
Jeon, Y.; Kim, G. E.; Lee, M.-G. (Ajou University) 147
- 3. Effective Calibration and Implementation of Galvanometer Scanners as Applied to Direct Metal Laser Sintering**
Land, W. S. (University of North Carolina-Charlotte) 151
- 4. Multi-Scale Evaluations of the Roughness of Surfaces Made by Additive Manufacturing**
Zeng, Y.; Wang, K.; Mello, B. C.; Wang, J.; Brown, C. A. (Worcester Polytechnic Institute) 157

Emerging Technology

- 1. Fundamental Study on the World's Thinnest Layered Micro-Stereolithography Using Evanescent Light**
Takahashi, S.; Tahara, H.; Miyakawa, K.; Takamasu, K. (The University of Tokyo) 163

Measurement Artifacts and Process Characterization

- 1. A Novel Test Artifact For Performance Evaluation of Additive Manufacturing Processes**
Hao, B.; Korkmaz, E.; Bediz, B.; Ozdoganlar, O. B. (Carnegie Mellon University) 167
- 2. In-Situ Target Surveying for Ink-Jet Printing of Functional Materials**
Trost, H.-J.; Christison, M. S. (MicroFab Technologies, Inc.) 173

Metrology and Computed Tomography

- 1. Fusion of Multi-Length Scale CT to Characterize a Pillar Array**
Divin, C. J.; Sain, J. D.; Martz Jr., H. E. (Lawrence Livermore National Laboratory) 177
- 2. Comparability of the Performance of In-Line Computer Vision for Geometrical Verification of Parts, Produced by Additive Manufacturing**
Pedersen, D. B.; Hansen, H. N. (Technical University of Denmark) 179
- 3. Metrology Challenges of Parts Produced Using Additive Manufacturing**
Saint John, D. B.; Jones, G.; Nassar, A.; Reutzel, E.; Meinert, K.; Dickman, C.; Palmer, T.; Joshi, S.; Simpson, T. (The Pennsylvania State University) 184

Microstructure

- 1. Identification of Mechanical and Fatigue Characteristics of Polymers Fabricated by Additive Manufacturing Process**
Corbett, T.; Lee, C-B.; Tarbutton, J. (University of South Carolina); Kok, T. (Delft University of Technology); Smith, S.; Villarraga, H. (University of North Carolina - Charlotte) 186
- 2. Optimization of SLM Structures with Respect to Crack Growth and Lifetime**
Reschetnik, W.; Riemer, A.; Richard, H. A. (University of Paderborn) 190

Precision Engineering

- 1. Squareness Measurement of a Coordinate Measuring Machine Using a Laser Interferometer System**
Lee, H.-H.; Lee, D.-M.; Yang, S.-H. (Kyungpook National University) 196

Precision Manufacturing of Optics Using Additive Manufacturing

- 1. Generative Tool Manufacturing for the Replication of Micro-Optical Components**
Uhlmann, E.; Hein, C.; Bergmann, A.; Oberschmidt, D. (Fraunhofer Institute for Production Systems and Design Technology (IPK)) 201

Process Development and Optimization

- 1. Control of Microstructural Evolution in Powder Bed Fusion Additive Manufacturing in Relation to Functional Properties of Metals**
Dillingh, B.; Hayes, G.; Hoppenbrouwers, M.; Westerwoudt, V.; van Baars, G. (TNO Technical Sciences) 205
- 2. Design Rules for Additive Manufacturing: Designing for the Process**
Elsbrock, S. (Linear Mold & Engineering, Inc.) 209
- 3. Relation Between Tip Size, Deposition Speed and Roughness in FDM Technology**
Ruiz-Huerta, L.; Ortega-Rodríguez, A.; Caballero-Ruiz, A. (Universidad Nacional Autónoma de México) 214
- 4. Enhancing Surface Finish and Dimensional Accuracy in Additive Manufacturing Using Global Adaptive Direct Slicing**
Sikder, S.; Barari, A.; Kishawy, H. (University of Ontario Institute of Technology) 219
- 5. Application Specific AM Technology Development for High-End Mechatronic Systems**
Van Vaerenbergh, J.; Thijs, L.; Van der Perre, W.; De Bruyne, T. (LayerWise NV) 221

Secondary Finishing Operations

- 1. Using Acetone Vapour Treatment to Improve Secondary Finishing Operations in Additive Manufacturing**
Sikder, S.; Kaji, F.; Barari A.; Kishawy, H. (University of Ontario Institute of Technology) 223



Technical Papers

GE Aviation Perspective on Precision Capabilities of Additive Manufacturing

Steve Rengers

Additive Development Center, Organization Leader, R&D Group

The engagement of additive manufacturing is now facing the reality of process capabilities. Machines are typically building with powder bed technologies layer thicknesses of 10 microns to over 50 microns. Given these discrete increments, obtaining a 10 micron feature or tolerance is challenging without secondary processing. While R&D systems are emerging with 1 micron layer thicknesses, 10 microns will still be a challenge in the as-built condition. Hybrid systems are emerging, combining additive and subtractive modalities that could enable tighter tolerance features. GE Aviation will provide an overview of our additive programs and how we are working on accepting the product of the process and the other downstream challenges of an additively built part on a macro scale of around 250 micron tolerances. Emerging technologies that have the potential to achieve sub-10 micron feature resolution will be overviewed.

Metrology Needs for Additive Manufacturing

Thomas R. Kurfess Ph.D., P.E
The George W. Woodruff School of
Mechanical Engineering
Georgia Tech
Atlanta, GA USA

John S. Taylor, Ph.D.
Lawrence Livermore
National Laboratory
Livermore, CA USA

Additive manufacturing presents interesting opportunities for rapidly making components that have extremely complex geometries. Such components have a wide variety of metrology needs that are not addressed by current measurement systems, data analysis techniques and metrology standards. This paper presents an overview of some of the most interesting and difficult aspects that additive manufacturing poses for metrology operations.

Geometric Analysis

The complex geometries that are generated by additive manufacturing processes pose a wide variety of challenges for metrology. The most obvious is that the shapes that are produced are often not comprised of simple geometric elements (e.g., circles, cylinders, planes, etc...). Thus, classical metrology tools such as micrometers, dial-gages and plug gages are typically not used for part verification. Rather, the approach for validation is often based on coordinate metrology. The generation of such coordinate points is typically done with non-contact scanning systems due to the often compliant or flexible nature of the thin-walled parts. The compliance of these parts is also often increased by the fact that many 3D printed parts are made of polymers. As a typical inspection of such parts is a least squares fit of a point cloud to a CAD model, thin walled flexible components present many difficulties for validation. One of the major difficulties that arise from the thin walled, flexible parts is that of point-to-surface assignment. For example, points taken from the outer surface of a thin walled sphere may easily be erroneously placed on the internal surface of the sphere.

From an analytical perspective, a least squares approach to point cloud to target model alignment is the typical approach that is used for complex geometries produced by additive manufacturing. However, least squares fitting does not provide assembly guarantees that zone fitting approaches such as maximum material condition, least material condition approaches provide. Thus, certain guarantees that are provided by approaches such as hard (go/no-go) gaging are not available, or are difficult to achieve at best.

Finally, many metrology systems employ knowledge of the manufacturing process to aid in determining error. For example, odd number lobes on a cylindrical part produced in through feed centerless grinding are expected and, therefore, identified during the inspection. Very little is known about the additive manufacturing processes in terms of process physics to provide such insight. Thus, it is anticipated that heretofore unmodeled process errors will be categorized as “apparently random” errors. This shortcoming should be alleviated as improved process models become available.

Digital Representation

Current additive manufacturing systems make use of a standard STL CAD model format. Thus, the actual part that is produced is a digitized (actually tessellated) model. One current concern is that the comparing metrology data to the original CAD model might result in inaccurate results. Rather, there is some discussion on comparing the tessellated surface to point clouds generated from inspection. Such an approach is well known in the industry via a variety of techniques including the classical one described by Besl and McKay. Such approaches have been demonstrated for several millions of points, as well as large number of surfaces. However, as the complexity of the models increases, as it will with internal honeycomb structures being use for both light weighting and material minimization, the complexity of comparing point clouds to CAD data will increase dramatically. If non-analytic representations are employed in the CAD model (e.g., NURBS) and inspection data are compared to CAD models rather than STL models, the inspection task becomes even more complex

Potential for In-Process Measurement

Additive processes by their nature, allow for in-process inspection of the internal structure of a part. Thus, if inspection is executed at every layer, it is possible to identify defects such as porosity and internal geometric errors on a layer by layer basis. Furthermore, if inspection occurs at every layer, the potential exists for in-situ process control at each layer. Such process control could include corrective actions on subsequent layers, or the removal and reapplication of a layer deemed to be out of specification.

Another interesting opportunity for metrology in additive manufacturing is the ability to generate digital voxels based models of the part being inspected. Such digital models employ voxels which are the 3D analog to pixels in 2D. Several issues do arise using such a representation. First, the amount of memory required for a voxel based representation has the

potential to be large. For example, a 1mX1mX1m volume divided into voxels that are 1 μ m results in 10^{18} voxels. That being said, at the most simplistic level, each voxel would represent the presence or absence of material. In such an instance each voxel would only use a 1 bit representation. However, just as pixels store color information, a voxel could be used to store other information beyond the presence or absence of material. For example, material properties might be stored in the voxel representation, providing a significant wealth of information on the part; but, yielding enormous quantities of inspection data. This provides significant opportunities for data compression and big data analytic research that integrates well into the Materials Genome Initiative. Finally, having a voxel based model, naturally transitions inspection data to a purely digital format (3D), much in the same manner as sound (1D) and images (2D) are digitized. This digital representation will enable digital processing of the 3D data in an efficient and easily parallelizable format. Basically, the digital format will allow technologies such as cloud computing, high performance/parallel computing and cloud storage to be easily brought to bear on the inspection data.

Material Properties

As already mentioned, if a digital/voxel based format is used, metrology information can be stored that are not only related to geometric properties, but other data may be stored such as material characteristic properties. This is a key point to understand as the materials aspects of additive manufacturing are often marginalized by the exciting geometric possibilities. However, additive manufacturing affords the ability to integrate multiple materials into a part during manufacture. Such information could easily be stored in each voxel. Other critical information might be stored in each voxels as well, such as environmental conditions and laser power at the time of the voxel's creation. Such information is critical in determining the functionality of the overall component, and may be used in subsequent components models for strength and performance evaluation. It is interesting to note that a voxel model of the inspection data is fairly analogous to FEA meshes used for structural and EM analyses as well as the STL (triangulated) models actually used in production.

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MODELING AND SIMULATION OF ADDITIVE MANUFACTURING PROCESSES

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INTRODUCTION

It is now possible produce a variety of metal parts quickly and with great complexity, but to transition from making prototypes and demonstration parts to parts that can be used in production requires the parts to be qualified and certified. Certification takes time and is a significant hurdle to be overcome. When our first additively manufactured parts go into production, we will use the same certification approach that has been successful in the past. In the future, alternate certification methods would be desirable to accelerate the certification process. To that end, we are applying the same approach that has been successful for stockpile stewardship to manufacturing. Process modeling and simulation will be coupled with focused experiments through data mining and uncertainty quantification. We are going to establish the understanding of process-property-performance connections with process-aware simulation tools capturing that understanding.

MULTISCALE PROCESS MODELING

While the machines that are used to produce additively manufactured (AM) parts are conceptually simple, the process is quite complicated involving a broad range of physical phenomena. Modeling of the process is complicated by the fact that the physical phenomena occur over a broad range of length and time scales. To address this, we are adopting a multiscale modeling strategy. The strategy embodies four models. Information passing is used to integrate the models. At the highest length and time scales is our effective medium model (EMM) where the part is resolved but the microstructure and the powder are homogenized. The EMM takes critical input from the other three models. Our powder model resolves all of the powder particles in the powder bed. It takes input on the powder

properties and laser parameters. Its output to the EMM includes powder packing information, thermal properties of the powder bed, and melt characteristics of the material.

Our microstructure model is intended to predict the microstructures that develop in the AM process. It takes input on the melt pool geometry and thermal profiles from the powder model. It passes solidification kinetics information to the EMM. Our process aware model is intended to use the detailed microstructural information provided by the microstructure model to predict temperature and rate dependent constitutive behavior for input to the EMM model. Eventually, this model will be used to connect the process with the properties and then to the performance of the material.

In this presentation, we show results from two of our models: the EMM and the powder model. We discuss how these models are being integrated with experiment using data mining and uncertainty quantification.

Effective Medium Model

Our effective medium thermomechanical model, based on the LLNL's Diablo code, has been used to build small parts at high resolution. Relevant time scales for a part to be built are minutes to hours and length scales are centimeters. In the example in Figure 1a, powder (in blue) is applied to a 1mm x 1mm base plate (in grey). The laser, moving at 180mm/s, traces a serpentine path transforming the powder to liquid (in red). It takes 32ms to complete a layer. A significant inertial lag is observed as the layer consolidates. The laser scan rotates by 90° in each new layer demonstrating how scan strategies can be studied. This simulation is used to predict properties such as residual stresses. Initial

results indicate that the residual stresses predicted using this model are consistent with our experiments that are being carried out both here and at the Los Alamos Neutron Science Center.

Powder Model

We are also developing a model at the scale of the powder, based on the Lab's ALE3D code, to answer questions such as "Can a powder be processed by AM and what are the optimal processing conditions?" This is particularly important as we move to a broader range of powders, not just the ones the additive manufacturing machines were designed for.

Our powder model is a mesoscale model of discrete powder particles in an ALE framework. The simulation covers time scales on the order of fractions of a second and length scales of a few millimeters. Figure 1b shows the temperature distribution on the surface as the laser spot moves to the right. Figure 1c is a cross section showing melt depth and velocities. Note the significant turbulence in the melt pool. We find that the physics is driven by the surface tension and its effect on the topology and heat conduction. It causes the melted particles to coalesce rapidly and form a smoother surface. This in turn increases the contact with the substrate, which transfers heat faster and cools the melted track.

Data mining and Uncertainty Quantification

Simulation and experiment in isolation are insufficient to accelerate certification. In the same way that the data mining and UQ techniques contribute to the certification of the stockpile, they will enable us to exploit the simulations and experiments to build and certify parts with desired properties.

CONCLUSIONS

We are leveraging existing codes for the development of next generation tools aimed at advancing the state of the art of AM. Our focus is on developing a deep understanding of the AM process and process-aware models to guide development of AM processes for a wide array of materials. In the longer term, this modeling will be essential to accelerating certification of AM parts. We note that industry and other government entities are facing the very same certification issues as we are. Thus we expect that the models that we are developing could also help others rapidly develop qualified AM

components, which could accelerate the adoption of AM in US industry and other government entities.

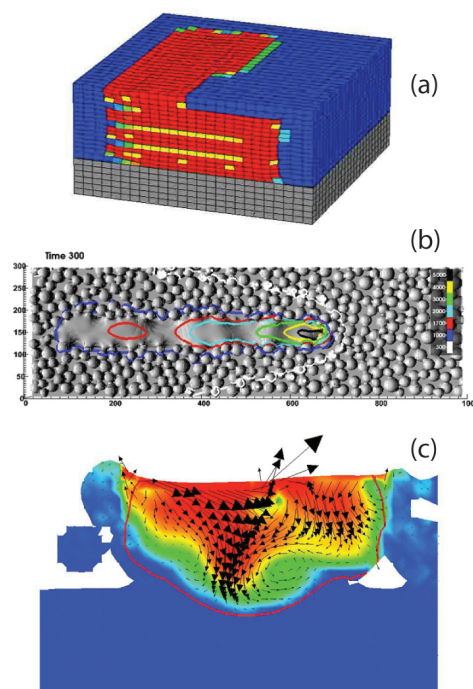


FIGURE 1. (a) Thermo-mechanical simulation as the eighth layer of 316L stainless steel powder is formed on a build plate. The model includes melting, consolidation and resulting residual stresses. This configuration leaves a boundary of material (on three sides) in the powder state to examine edge effects. This approach of effective medium modeling is required to reach simulations of part-scale geometry. Laser melting of a random packing of nominally 27-micron particles, showing consolidation by surface tension and gravity. The color represents temperature. The molten pool is visible in (b) and the recirculation of the liquid metal is visible through the arrows in the cross section in (c).

ACKNOWLEDGEMENTS

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TOPOLOGY OPTIMIZATION AND ADDITIVE MANUFACTURING, NATURAL COUNTERPARTS FOR PRECISION SYSTEMS

State-of-the-Art and Challenges

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ABSTRACT

After pioneering research in the late eighties, topology optimization gained major interest from the structural optimization community. In topology optimization, the layout of a structure is automatically created by an algorithm which tries to optimize a response, e.g. compliance or deformation, while satisfying certain constraints, e.g. eigen frequencies, mass etc. In fact, topology optimization seeks an optimal placement of material, leading, besides the layout of a structure, to shape and dimensions as well. Early industrial adopters can be found in automotive and aerospace industry.

Topology optimization typically relies on finite element models. The topology is reflected by one or more design variables introduced for each finite element. Consequently, such a design discretization leads to a voxel-based design representation. For computational

efficiency so-called adjoint design sensitivities are used, which provide essential information to the optimizer.

Topology optimization is capable of producing very complex 3D structures, outperforming designs created manually. The voxel-based design representation implies that the resulting designs are, potentially, immediately ready for additive manufacturing. Moreover, complexity of the designs is often even unsuited for classical production technologies. See Figure 1 for an example.

From the perspective of additive manufacturing, application of topology design unleashes its full potential in terms of design freedom. The superior performance of complex topology optimized parts forms a strong incentive to use additive manufacturing. This holds in particular for complex mechatronic precision systems where multiple physical domains interact, and



Figure 1: Complex alternated gripper. This complex 3D compliant mechanism was designed with topology optimization and produced using additive manufacturing.

where assembly is reduced by functional integration in monolithic components.

Application of topology optimization in combination with additive manufacturing is an obvious step to be taken for mechatronic precision systems. For sure, this combination will lead to better performance. The geometric complexity of components will drastically increase. Conversely, the number of assembly steps will reduce. The application of additive manufacturing will lead to improved functional integration. A case study for a precision stage is shown in Figure 2.

In this presentation we will briefly introduce topology optimization and its potential in combination with additive manufacturing. Next, we put focus on precision mechatronic systems. In this context, we shall review the state-of-the-art in topology optimization and identify the associated main challenges. Aspects that will be highlighted in this review are:

- The performance of precision systems should typically be extracted from a transient response. This causes severe complications for topology optimization, in particular for high resolution and multi-physics problems.
- To reduce or eliminate manual redesign, process modeling and manufacturing constraints should be integrated in the topology optimization.
- High performance precision systems typically involve multiple physical domains and nonlinearities.
- Detailed 3D structures call for high resolution design discretizations, which has a very pronounced effect on computer time.

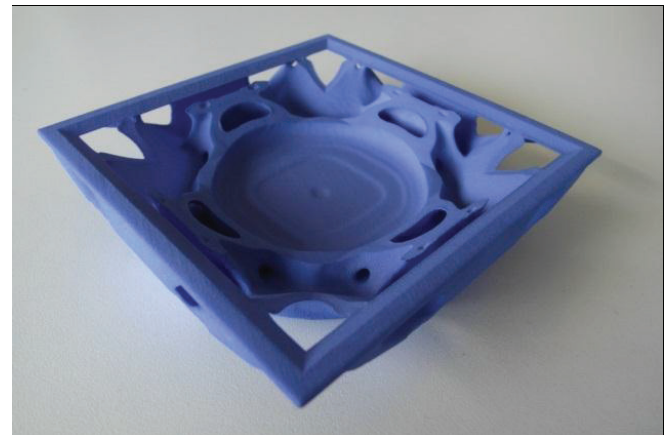


Figure 2: Mockup of the interior of a precision stage. The upper half of the stage has been removed. Topology optimization was applied to optimize the dynamic performance. The complex 3D geometry of the structure can only be fabricated economically using additive manufacturing.

Metals-Based Additive Manufacturing: Metrology Needs and Standardization Efforts

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INTRODUCTION

In recent years additive manufacturing (AM) has received significant visibility, both in the popular media as well as in scientific journals. In fact, the number of publications on additive manufacturing (including 3D-printing) jumped from approximately 1,600 in 2011 to over 16,000 in 2012 [1]. Additionally, impressive *niche* successes, such as a metal jaw replacement made completely via additive manufacturing [2], contributes to the fervor that makes up the future vision for additive manufacturing. This vision for additive manufacturing is simultaneously imaginative, outrageous, and inspiring. And while it is difficult to accurately predict the full future impact of additive manufacturing, it is easy to imagine how it *could* potentially impact every major industry – aerospace, defense, medicine, transportation, food, fashion – and have an even bigger impact on U.S. manufacturing than the robot revolution. [3].

While this vision is impressive, there remain significant technical challenges that first must be overcome if this vision is to be fully realized. This paper will summarize the key metrology-based technical challenges that are preventing metals-based additive manufacturing processes from being more pervasive, and describe current standardization efforts that are underway to address these challenges.

ROADMAPPING EFFORTS

Collaborative roadmapping efforts have helped capture and define the most important technical hurdles that are preventing the vision of additive manufacturing from being realized today. These efforts include a roadmap development sponsored by the National Science Foundation in 2009 [4] as well as a more recent effort that focused on metals-based additive manufacturing [5]. Both of these activities included broad participation from industry, academia, and government, and the list of challenges resulting from these activities had a high degree of

overlap. Most of these challenges will require a significant metrology effort, if they are to be successfully solved. The following summarizes the key technical needs developed in these roadmapping efforts as they apply to metals-based additive manufacturing processes:

Material Properties

The material properties of parts made via additive manufacturing are not well understood and there is a lack of high-quality, pedigreed data necessary for using AM parts in high-stress applications such as turbine blades or jet engine components. There is also a lack of understanding on the relationship between powder properties and part properties. In addition, currently there are very few commercial powders available for use in metals-based AM systems.

Process Understanding

Although many metals-based processes involve heating, melting, and cooling of metal – which is understood at a fundamental level – the difficulties in measuring these processes *in-situ* result in a lack of process understanding, and difficulties in optimizing the processes. Many of these processes also have large day-to-day variability.

Qualification and Certification

There are currently no standardized methods for qualifying and certifying AM input materials, processes and parts. Current empirical methods for qualifying parts are unwieldy and impractical for AM, due to the large number of test samples required and the large number of process parameters.

Part Accuracy and Surface Finish

The accuracy and surface finish of AM metal parts is generally poorer than that of traditional material removal processes.

Fabrication Speed, Build Volumes and Part Size

AM processes are generally slow, and the build volumes and part sizes are limited.

Lack of AM Standards

Currently there are very few additive manufacturing-specific standards that have been developed in a consensus method through a standards development organization (SDO).

Data Formats

Currently there are only two general data formats in use, one (STL) that is widely used but has some limitations, and another (AMF) that overcomes some of the STL limitations but is not widely used due to the limited number of systems that are compatible with it.

STANDARDIZATION EFFORTS

AM standards are essential if AM technologies are to achieve wider use. Standards provide technical correct and consistent methods, which if followed properly, give the confidence that everyone in the industry is doing things the same, correct way.

Despite there being few AM-specific standards in existence today, the current state of affairs for AM standards development is very favorable. There already exists two relatively new SDOs for AM, the ASTM-I F42 Committee on Additive Manufacturing Technologies, and its sister committee, ISO TC261. Fortunately we are also still in a very early phase of AM technology development, which allows for strategic planning of which standards are needed, and when they should be developed. Such strategic planning is already taking place between ASTM-I F42 and ISO TC261. In fact, F42 and TC261 have a unique agreement that allows them to co-develop and co-brand standards. This favorable standards development situation will also minimize the need for future standards harmonization efforts, which are often slow and laborious.

Additionally, in many cases, existing standards (e.g., for measuring powder and part properties) can be used as the basis for AM-specific standards, either as currently written or with some minor adjustments. This already existing base of standards will greatly accelerate the development of AM-specific standards.

SUMMARY

There are significant technical hurdles, many of which require metrology-based solutions, which are hindering the full vision of AM from being realized today. These challenges will require collaborative, inter-disciplinary efforts to solve. One hurdle is the lack of AM-specific standards. However, the current SDO infrastructure in place to develop these standards is well-suited to do so.

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OPTIMIZATION OF MEDIA FEED CHANNELS IN LASER BEAM MELTING

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ABSTRACT

In this paper the Laser Beam Melting (LBM) technology is applied to manufacture very complex components. LBM is a neutral and independent term for a technology which is also known as company related names such as Direct Metal Laser-Sintering (DMLS). According to ASTM 2792-12 – LBM belongs to the process category of powder bed fusion of metal powders. In general Additive Manufacturing (AM) differs from conventional technologies by its additive joining material to a physical part in layers instead of removing or forming material. Here the characteristic additive build-up at LBM provides the opportunity to combine and integrate media feed channels in pilot burner tips for gas turbines. As a result of this, conventional manufacturing processes, with comparatively short production times, can be substituted by the LBM process. Furthermore own investigations also illustrate that besides the chosen orientation in the build chamber also the material and the process parameters have a strong influence on the quality of the components.

INTRODUCTION AND STATE OF THE ART

Internal cooling channels for conformal cooling purposes are already considered as state of the art in the tool and mold making industry by applying the LBM technology [1]. However, process-specific limitations exist for the manufacturing of small media feed channels with high requirements regarding low-tolerance mass flows. Also modern industrial gas turbines have to fulfill a number of different boundary conditions such as high efficiency combined with low overall cost per kW, reliability and compliance to emission standards. This requires sophisticated combustion systems to enable the compliance to low NO_x and the firing with natural gas and/or liquid fuels. One of the key components in the com-

bustion system is the pilot burner which is illustrated in FIGURE 1.

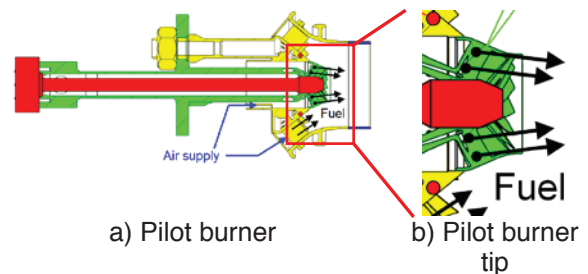


FIGURE 1. Pilot burner.

Often this part is assembled out of a number of single pieces which are joined by brazing or welding procedures. Specifically the burner tip receives a lot of development effort to allow the perfect mixture of air with fuel. Complex guide vane designs are employed, combining aerodynamics with fluid and thermodynamics to provide the gas flow with a swirl. Holes in the axial swirler vanes enable gas injection into the flow path, an efficient mixture of fuel and air and a high power output, while meeting highest emission and efficiency standards. The design of the gas exit holes in the guide vanes, both in diameter and shape are critical to achieve the overall design criteria. The design of the whole assembly is a challenge per se for conventional manufacturing procedures. To realize this design, advanced manufacturing technologies such as Laser Beam Melting are key enablers to meet stringent technological and manufacturing cost efficiency goals. Since the LBM process offers a unique potential to combine complexity with manufacturing cost effectiveness the goal of this study is to investigate the ability of the LBM process to manufacture the whole part with integrated media feed channels in the requested design tolerances. Due to the process characteristics there are shape and dimensional deviations of channel structures (cf. FIGURE 2).

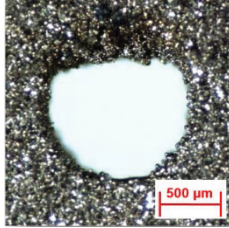


FIGURE 2. Geometrical deviation of a LBM channel structure with a diameter of 1 mm [2].

To overcome these kinds of problems Mercelis [3] developed in 2007 an approach to avoid geometric deviations like the material collapse at overhang areas by the local adjustment of the exposure parameters.

PRELIMINARY CONSIDERATIONS

The experimental procedures are performed using the material Hastelloy X. This nickel-based alloy is suitable for high-temperature applications and it is commonly used in a wide range of conventional components because of its excellent manufacturability and weldability. [4]

To avoid a metallurgical inhomogeneity and to avoid differences in the mechanical behavior of LBM components made of Hastelloy X, a variation of the local exposure parameters is not applied in this studies for the optimization of media feed channels. Here another approach is used which can be applied by the majority of operators without cost-intensive and specialized software and operating tools. It is based on a geometrical optimization of the circular cross sections of the channels. The aim is to investigate a curve which replaces a circular cross section in the CAD data and which can be mathematically described. At the end this procedure should lead to a perfect circular LBM media feed channel.

EXPERIMENTAL SETUP

Effect of the Orientation on the Geometric Shape

The geometric position of individual channel geometries cannot be influenced easily due to the complex geometries of the LBM components. Against this background, the predominant material collapse is analyzed in detail as a function of the orientation in the build chamber. The analysis is performed on cross-sectional geometries with a diameter of $D = 1 \text{ mm}$. The test specimens are manufactured in various part orientations (rotation angles φ und Θ) in the build chamber (cf. FIGURE 3).

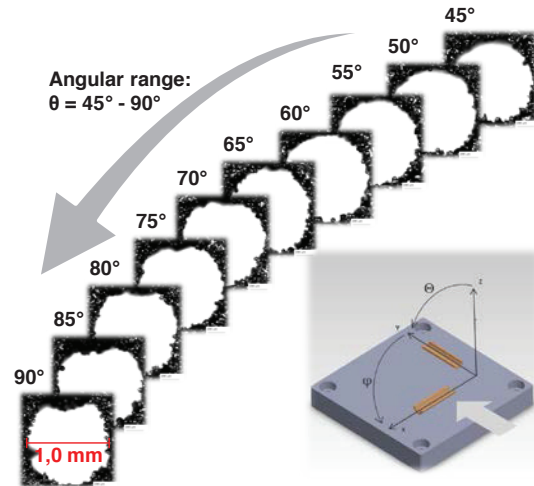
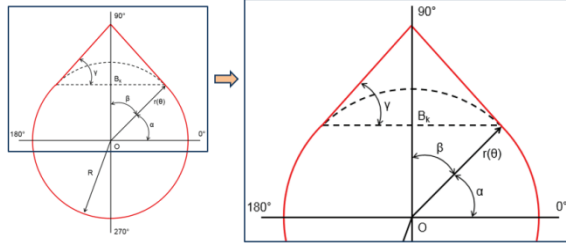


FIGURE 3. Cross-sectional geometry as a function of the polar angle Θ .

Due to symmetry effects, the angular range of the azimuth angle φ varies between 0° and 90° , whereas the polar angle Θ varies between 45° and 90° . The analysis results in the independency of the material collapse when rotating around the azimuth angle φ and the very strong dependency when rotating around the polar angle Θ . It turns out that the material collapse decreases with decreasing polar angles Θ from 90° to 65° . This latter angle represents a boundary value of the polar angle Θ because no material collapse is recognizable at smaller polar angles. This effect can be explained by the thermal balance of the layered structure. With decreasing polar angles Θ the exposed surface ratio of successive layers changes and with it the heat dissipation into the solid material.

Geometric Optimization Approach

The geometric optimization approach follows the idea to replace the circular cross section of the media feed channels by a rectangular-shaped geometry (cf. FIGURE 4). On the one hand this approach increases the process stability of the manufacturing of media feed channels in LBM and on the other hand the decreased overhang structures also lead to decreased material collapses. In particular, the last layers at circular cross-sections have big overhang geometries and represent an increased risk for a process breakdown. Avoiding these extreme overhang structures by this approach reduces the risk of a collision between the recoater and the components.



$$r(\theta) = \frac{b}{\sin\theta - K_1 \cdot \cos\theta} \quad \left(\alpha < \theta < \frac{\pi}{2} \right)$$

$$r(\theta) = \frac{b}{\sin\theta - K_2 \cdot \cos\theta} \quad \left(\frac{\pi}{2} < \theta < \pi - \alpha \right)$$

$$r(\theta) = R \quad (0 < \theta < \alpha \text{ and } \pi - \alpha < \theta < 2\pi) \text{ with}$$

$$b = R \cdot \sin\alpha - K_1 \cdot \frac{B_k}{2}$$

$$K_1 = -\tan\gamma \quad \text{and} \quad K_2 = -K_1$$

FIGURE 4. Divided circle with rectangular-shaped geometry (auxiliary geometry).

Smaller overhang angles lead to decreased material collapses and this in turn simplifies the calculation of the optimization of the geometry. The design of the rectangular-shaped geometry is intended to reduce the collapse of the material in a way that its shape after production equals the perfect shape of a circular geometry. For a full description of the auxiliary geometry the angle γ and the width B_k can be used which are depending on the dimensions and orientations. In this case the angle γ influences the shape of the auxiliary geometry and also varies with the orientation of the polar angle Θ . The diameter-dependent width B_k results from the critical overhang length. This also represents the diameter independent critical angle, which affects the conformal manufacturing.

Definition of a Correction Function and Implementation in Creo Parametric

The implementation of the correlations described above in an Excel-based macro allows the automated output of the desired geometrical adjustment in form of calculated functions. For this purpose the desired channel diameter and the orientation of the channel axis in the build chamber are indicated. With declaration of a specific diameter the associated critical width B_k is determined and kept constant regardless of its orientation. The input of the polar angle Θ provides the appropriate correction angle γ . Both angles are depending on each other – the smaller the polar angle Θ , the smaller the correction angle γ . Since the geometric shape of the corrected channel geometry varies depend-

ing on γ and Θ the design is simplified for the 3D CAD software Creo Parametric by a User Defined Feature (UDF). After being created it is available in the UDF library like the standard features in Creo (e.g. bore or chamfer). [5] [6] The transfer of the calculated functions of the curves to the CAD software is made by the application-specific interface programming software VB API (Visual Basic Application-Programming-Interface). The generated application is an executable file (.exe). Immediately after running the program the geometry defining parameters are prompted. Here the input of the desired diameter and the polar angle in the range between $\Theta = 0^\circ$ and $\Theta = 90^\circ$ is made.

Using the interface described above the contour of the corrected channel geometry can be sketched within the assembly. Subsequently the 2D sketch contour is projected according to the feature "profile" in a defined length and the 3D volume cut of the material is generated which represents the corrected channel geometry in the CAD model (cf. FIGURE 5).

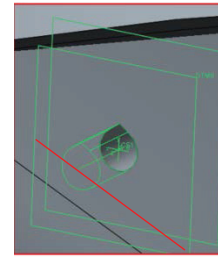


FIGURE 5. Volume cut of material in CAD model.

RESULTS AND DISCUSSION

Validation of the results

The validation of the results is carried out in two stages. First, the corrected channel geometries are visually inspected. Here the main focus is the geometrical shape as well as the dimensional accuracy of the cross-sectional areas. The images needed for this purpose are derived from 3D computer tomography (CT) scans. In the second validation step, the cross-sectional areas are evaluated in a test rig for mass flow measurements. The focus of this investigation is the calculation of the effective cross-sectional areas (A_{eff}) of the various dimensions and orientations. The effective cross-sectional area is considered to be the definitive benchmark while comparing both, the conventional manufacturing and Additive Manufacturing.

CT-Examination

To compare the corrected and uncorrected cross-sectional geometries a test body is designed with an integrated media feed channel and manufactured afterwards in both variants. The geometry is designed in such a way that the basic curve of the channel covers a polar and azimuth angle in a range of 0° to 90° in each case. Thus the effect of different auxiliary geometries can be illustrated in different sectional planes and can also be compared to the uncorrected channel design (cf. FIGURE 6).

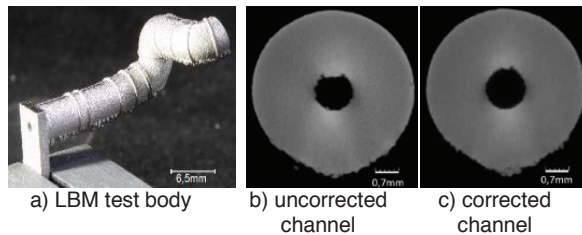


FIGURE 6. Test body for CT scan ($\Theta = 90^\circ$ and $\varphi = 0^\circ$).

As illustrated in FIGURE 6 the corrected channels have a circular cross shape (c) whereas the uncorrected channels (b) have a material collapse on the top. The utilization of the correction functions consistently provides good results for every possible polar and azimuth angle combination. Also the independence of the azimuth angle is determined.

Flow Measurement of A_{eff}

In a second step the developed correction functions and with it the circular cross-sections are validated by flow measurements using different orifice plates. The completed test rig can be seen in FIGURE 7.

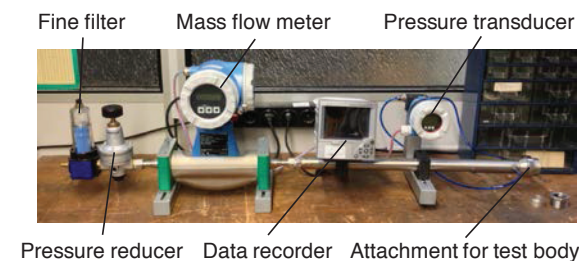


FIGURE 7. Test rig for flow measurement.

The aim of this measurement is to determine the effective cross-sectional area A_{eff} of a media feed channel. [7] [8] Punched discs with different patterns of holes and different diameters serve as orifice plates. The geometric surface area of the holes is kept constant, while the number of

holes is increased from one to 20. In order to compare the results of the corrected ($dmls_c$) and uncorrected ($dmls_uc$) LBM channels with conventional manufacturing methods, the test specimens are also lathed_eroded and DMLS_eroded. At constant back pressure, the influence of the manufacturing process is examined regarding the resulting effective cross-sectional area. The determined relative effective cross-sectional areas A_{eff} of the different test bodies are shown in FIGURE 8.

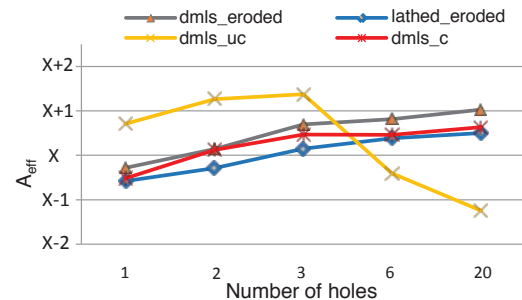


FIGURE 8. Effective cross-sectional area A_{eff} of different test bodies.

As illustrated the method of manufacturing of the test bodies leads to different measurement results. Thus, the determined effective cross-sectional areas A_{eff} of the DMLS_eroded test bodies are 2.77 % (in average) higher compared to those which are lathed_eroded. This interesting observation is due to the different nature of the inlet edges. The edge property resp. quality of subsequently implemented holes in LBM test bodies can be described as sharp-edged according to the definition given in DIN ISO 13715 [9]. Nevertheless further studies show that the geometric nature of the edges consistently have an abrasive character. The sharp edges produced with conventional manufacturing, cannot be achieved with LBM due to the characteristics of the process. The inlet edges at the DMLS_eroded test bodies improve the flow profile at the channel inlet and lead to increased effective cross-sectional areas. With regard to the flow measurement of A_{eff} another validation test is carried out which investigates the geometrical optimization approach for tilted test bodies. The test bodies have 20 holes fixed diameter. Circular cross-sections of these small dimensions have the greatest need for correction according to previous studies. The need for correction is sufficient for the circular cross-sections with a diameter of about $D = 1$ mm from a polar angle of $\Theta = 90^\circ$ to $\Theta = 70^\circ$. The polar angle Θ is decreased stepwise in 1° -steps, so

the batch consists of 20 test specimens (cf. FIGURE 9).

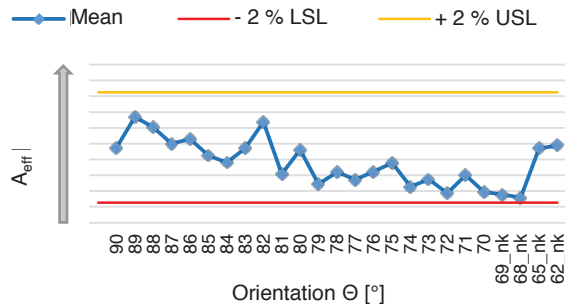


FIGURE 9. A_{eff} for angle-specific correction functions.

In addition, four samples within the angle range of $\Theta = 69^\circ$ - 62° are tested without geometry optimization for the verification of the selected threshold of this test series. The determination of a suitable reference value is carried out by three separately manufactured test specimen with an orientation of $\Theta = 90^\circ$.

The curve shows the normalized cross-sectional area A_{eff} in dependence of different orientations in the range of $\Theta = 90^\circ$ - 70° . The results of the flow measurements confirm the correction functions described above. To verify the polar angle range of $\Theta = 90^\circ$ - 70° for the utilization of the correction function even more specimens are manufactured without the correction functions. Here the polar angle is smaller than 70° . The specimens are named 62_nk, 65_nk, 68_nk and 69_nk. As you can see in FIGURE 9 these specimens show a tendency towards the middle of the diagram. So there is no need for any correction functions, which verifies the angle range mentioned above. Also all examined test specimen only vary between the specified limits.

SAMPLE APPLICATION

In this chapter a practice-oriented sample application, a pilot burner tip, is made by LBM taking into account the correction functions and geometries described above. This pilot burner tip model has multiple fuel channels which are uniformly arranged axially around the main axis. They also guide the combustion gas into the swirler vane profiles (see FIGURE 1).

The atomization of the fuel takes place through small fuel injection holes. at five small outlet holes on the vane's surface. One of the major challenges for the Additive Manufacturing of such components is to ensure low-tolerance mass flows in the pressure-specific fuel supply through the injection holes. A uniform feeding is

essential for ensuring the desired and controlled flame formation.

The measurement results of the pilot burner tips have a significant difference in terms of the resulting effective cross-sectional area A_{eff} . Thus the cross sectional area of the conventionally made burner has been set as a base line. Compared to this result the LBM burner has a 6.38 % (in average) higher effective cross-sectional area. In order to analyze this mass flow deviation, a variety of fuel channels of each pilot burner tip are measured separately (cf. FIGURE 10) to determine the scatter.

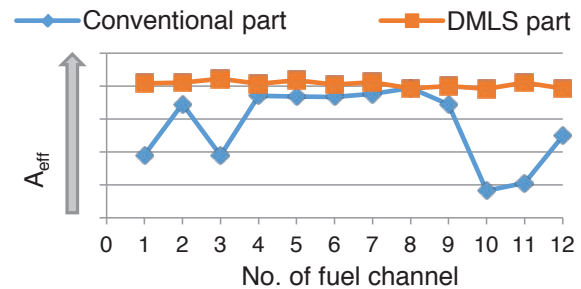


FIGURE 10. A_{eff} of single fuel channels.

When looking at the two graphs in FIGURE 10 it is striking that the blue line of the conventionally made burner channels has already a deviation of max. 18.4 %. The orange line for the DMLS channels is very smooth and does not show strong deviations between separate channels. However, to be able to give a reference the nearly parallel running channels of the conventionally made burner are used to calculate the average value. Since the deviations of the DMLS channels are very low the average value is calculated using all twelve channels. FIGURE 11 shows the results of the comparison of this measurement series.

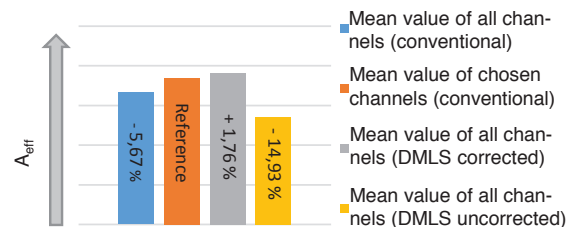


FIGURE 11. Mean values of A_{eff} for different pilot burner tips.

As you can see in FIGURE 11 the effective cross-sectional area A_{eff} of the conventionally made burner is increased by 5.67 %. This increase results from the exclusion of the chan-

nels which have extreme deviations from each other. Also the mean value of the effective cross-sectional area of the corrected DMLS channels is 1.76 % higher compared to the reference value of the conventional channels.

For a final comparison and in addition to the results obtained, the pilot burner tip is also manufactured by LBM without utilizing the correction functions. In this context it is noticeable that also here the deviations between different channels are very low. However, here we have a significant decrease of the effective cross-sectional area which is 16.42 % below the values of the corrected DMLS channels and 14.92 % below the reference value. This result illustrates how important the developed correction functions are in practice.

CONCLUSION AND OUTLOOK

Overall, the results of the investigated measurements are very satisfactory for future applications of the Laser Beam Melting technology as one representative of Additive Manufacturing. Even with complex functional parts such as the measured pilot burner tip, the determined correction functions and geometries of the media feed channels could be applied very successfully. Thus, the measured values of the effective cross-sectional area A_{eff} of the corrected DMLS pilot burner tip only varies 1.76 % from the conventional made pilot burner tip and is inside of the required tolerance. In addition, the new approach also achieved more consistent results of the individual media feed channels made by LBM compared to the conventionally made media feed channels.

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Verification of Design Rules for Additive Manufacturing

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INTRODUCTION

Additive manufacturing (AM) processes are increasingly integrated into today's value-added chains and are prospectively used for batch production. Due to the fact, that conventional manufacturing restrictions do not apply to AM processes, they offer designing freedom to realize feature-integration, undercuts and customized product development [1], [2], [3]. However, the design process has to consider specific restrictions, to exploit the full potential of AM. Applicability and performance of the used material as well as the AM process itself are influencing factors. Therefore the quality of geometric features has to be assessed. The state of the art validation results only in information about the materials mechanical properties. Geometric tolerances and limitations are disregarded up to now.

OBJECTIVE

The design process, considering specific AM restrictions, requires an assessment tool of AM design characteristics [4], [5]. The instrument to be developed allows designers and manufacturing engineers to estimate scaling options and production limits of different design features. This offers the implementation of an AM-oriented component design, appropriate to operational demands in the use of new materials within the selective laser beam melting (SLM[®]) process (FIGURE 1). Beyond that, it will help to strengthen confidence and invalidate reservations about additive manufacturing.

PROCEDURES

As FIGURE 1 shows, the designer and manufacturing engineer in the design phase should have the knowledge about mechanical properties of the used material and the minimum limits for geometric features. In order to create

the products with a robust process, it is necessary to capture the conditioning of used powder material. This powder analysis is needed to reduce the faults like a wider dispersion of mechanical properties or residual moisture.

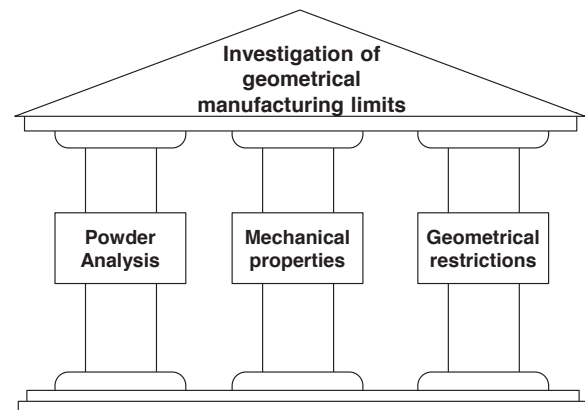


FIGURE 1. Investigation of geometrical manufacturing limits for AM.

In the following sections, the results of the investigations of tool steel 1.2709 are shown. For an adaptive design of new products, the analyses focus on mechanical properties, geometrical restrictions and the powder material conditions.

Powder Analysis

Before starting the actual building process, it is necessary to examine the condition of the powder. In particular, this serves quality management. The goal is to prevent possible errors in the chemical composition, particle shape, particle size distribution or moisture contained in the powder. Furthermore, these studies serve as a reference and comparison value, when the manufacturing engineer has to control the condition of his powder material.

The powder analysis on material 1.2709 was carried out according to DIN 3252 and VDI 3405 standards in order to qualify the material for AM processes. Further investigated powder requirements were:

- Grain size distribution (DIN ISO 4497)
- Rounded grain shape (DIN 3252)
- Powder Fluidity (DIN EN ISO 4490)
- Fine grain surface with less addition particles (SEM)

FIGURE 2 shows that 75 percent of the grain size are smaller than layer thickness of 50 μm and the normal grain size distribution is between 10 μm to 50 μm . The needed spherical particle shape with a middle diameter D_{n50} of 27 μm is given (FIGURE 3).

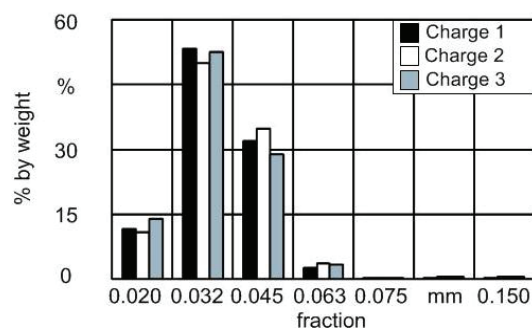


FIGURE 2. Grain fraction and percentage of the mass (dry sieving).

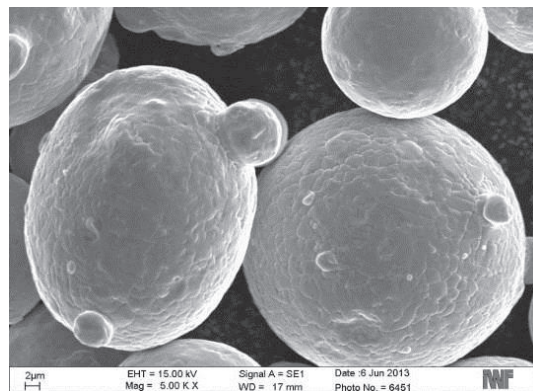


FIGURE 3. Spherical particle shape SEM-shooting (5000 fold amplification).

Mechanical Properties

For the development of new AM products, the selection of a proper material is significant. The material selection has to consider the AM process as well as possible subsequent material

removal or joining processes. In a next step, attention has to be paid to the additive manufacturing process itself. That means the orientation of components has to be considered in relation to the build-direction within the building chamber, for example. The options for heat treatability have to be kept in mind. In a subsequent review, the material-specific properties such as mechanical strength values and micrographs were investigated. FIGURE 4 shows the produced tensile specimen. The tensile specimen are structurally oriented at polar angles of 0° (upright), 45° and 90° (horizontal), each at an azimuth angle of 45°. To determine the influence of the angle configuration to the tensile specimen, ten of each type obtained heat treatment. Thereto five specimen of each type were solution annealed to reduce residual stress and to increase mechanical strength and five of each type were age hardened. The tested properties show ultimate strength and ultimate elongation.

TABLE 1 shows the procedure and conditions of the heat treatments.

TABLE 1: Heat treatment-procedures.

Heat treatment	Solution heat treatment	age hardening
soak time t_s	~ 2 h	~ 12 h
hold time t_h	1 h	6 h
cooling down time t_{dw}	~ 12 min	~ 2 h
soak time temperature T_s	0...824°C	0...500°C
hold time temperature T_h	~ 824°C	~ 500°C
cooling	fast cooling gradient	controlled ca. 2°C/min

By solution heat treatment the mechanical-technological properties are changed.

The untreated specimen have a range of ultimate strength between 980 N/mm² (90° build direction) and 1052 N/mm² (0° build direction). Specimen built with an angle of 45° have the highest ultimate elongation up to 5 % with a standard deviation. After the solution heat treatment the ultimate strength does not increase, but the ultimate elongation is increasing from 5 % to 7 %. Artificial ageing increases the strength factors approximately by twice the default value. In comparison with results of non-treatment and solution heat treatment of specimen the elongation decreases severely. Examining the brittle fracture of the standing specimen, an elastic behavior can be seen. After the two steps of heat

treatment the residual stress decreased and the strength increased by a factor of two. The anisotropy is still given.

The results show that a heat treatment is required following the additive fabrication and performs to demonstrate improved properties. Furthermore, it becomes clear, that the orientation in building chamber plays an important role. Components which are built vertically have reduced strength compared to the underlying components.

In sum, there is to state, that both designing and manufacturing engineer have to take several factors into consideration, regarding the mechanical properties of components to-build-by AM, such as the building process, positioning on the platform, post processing and heat treatment.

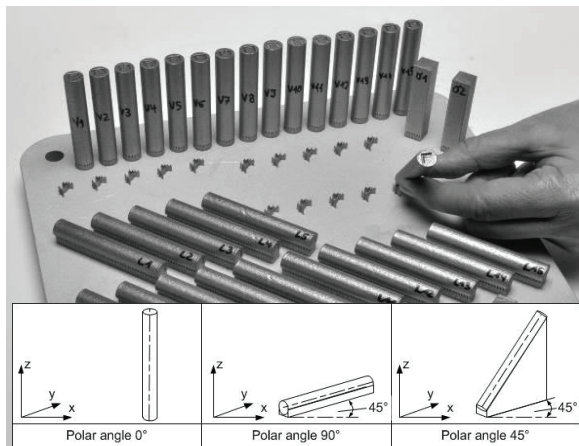


FIGURE 4. Produced tensile specimen with different orientations, material 1.2709.

Geometrical Restrictions

Limits for minimum feature sizes are important parameters for the designer. The boundaries of manufacturing depend on the chosen manufacturing process and parameter set and also on the orientation of the component in building chamber. In order to design the components, for the engineer it is important to know the minimum manufacturable limits. The aim is to meet the component requirements with the selected manufacturing process and material.

The authors analyzed several studies [4], [5], [6], [7], [8], [9], [10] as well as DIN standards (DIN ISO 2768) regarding geometry, positioning and classifying tolerances of AM and related processes like laser sintering and casting. A test structure of elementary geometric shapes like wall thickness, angle, overhang and radius was

developed (TABLE 2). These shapes and their predefined gradations were examined for surface characteristics. For this purpose, elementary features and basic elements, with inherent information of production-oriented design, were identified.

TABLE 2. Elementary geometric shapes and sizes.

shape	deviation	increment
wall thickness	$s = 0.05; 1 \dots 2 \text{ mm}$	0.1 mm
holes	$d = 0.05; 1 \dots 2 \text{ mm}$	0.1 mm
clearances	$s = 0.05; 1 \dots 2 \text{ mm}$	0.1 mm
cylinder	$d = 0.05; 1 \dots 2 \text{ mm}$	0.1 mm
radii	$r = 0.5; 1 \dots 10 \text{ mm}$	1 mm
slopes	$\alpha = 5 \dots 90^\circ$	5°

To capture the manufacturing limits, accuracy and the alignment dependence of the SLM[®] process, geometrical bodies with defined edges at several levels and orientations were generated. In order to save resources, machining time and versatility for most machines, all elements were configured on one platform with the dimensions 150 x 150 mm. To illustrate the test component, on the selective laser melting machine SLM[®] 250^{HL} of SLM Solutions GmbH, Lübeck, Germany with a ytterbium fiber laser an example was built using the tool steel 1.2709 (FIGURE 4).

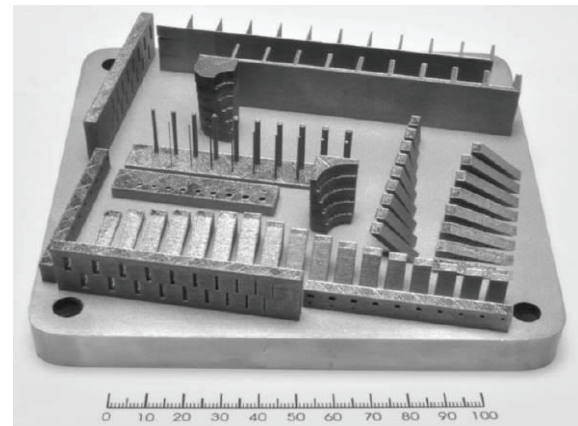


FIGURE 4. Component to verify design rules in AM.

The component was manufactured with proven conventional process parameters and without any supporting structures to investigate the basic machine behavior (TABLE 3).

TABLE 3. Process parameters.

condition	value	unit
Oxygen content	0-2	%
Laser wave length	1100	nm
Laser power	295	W
Scan speed	730	mm/s
Exposure strategy	chess	-
Coater velocity	500	min ⁻¹
layer thickness	50	μm
middle grain size D _{n50}	27	μm

Measuring and Analysis

The evaluation of subsequent measurements of the test component with optical and tactile systems allows the comparison of nominal and actual values. Available for the disposal of this study were the Zeiss Calypso coordinate measuring machine (tactile) and the ATOS Triple Scan, the latter generated the illustration shown in *FIGURE 5*. The light green and yellow areas indicate the variance of nominal conditions. This comparison allows engineers and designers to consider and support the design process decisions.

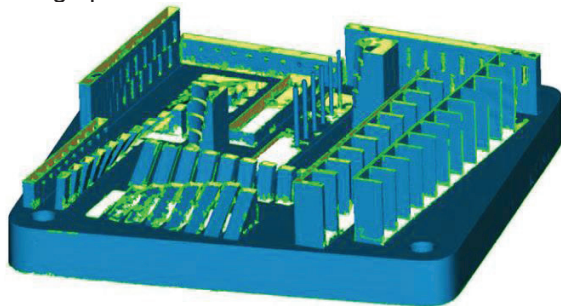


FIGURE 5. Optical 3D-measuring (ATOS) of the component to verify design rules in AM.

In the next step, the classification of the results was conducted for every single element on the component (*FIGURE 6*).

Specified size [mm]		0,05	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
Plane/Orientation	xy											
	xz											
	yz											
		1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2,0	
	xy											
	xz											
	yz											

FIGURE 6. Classification of measurement results exemplary on visual evaluation of wall thickness.

RESULTS

Geometrical manufacturing limits

The developed components supply core values for basic elements of geometric shapes which are producible with AM. A systematic arrangement of these shapes on the platform is important to submit a fast measurement and analysis. Therefore, minimal distances between the elements and maximal frame sizes are necessary and need to be regarded. Furthermore, the small internal structures like holes and clearances are too complex for most measuring systems and interpretable only with optical qualitative methods. A critical orientation of the basic elements was found only for the XY-plane of the wall thickness and was a result of the functional interaction of coater and baseplate (*FIGURE 7*). However, there were further subtle distinctions of conditions at the installation building chamber in consequence of the small baseplate.

Noticeable is the physical limit of the cylinder diameter minimum. This diameter is limited by grain size and laser beam diameter. Beyond that, the tactile measurement is only possible from $\varnothing = 1.1$ mm due to the touch pressure of the measurement system. The evaluated geometrical restrictions for AM are:

- Holes > 0.4 mm
- Clearances > 0.3 mm
- Wall thickness > 0.1 mm
- Slope surfaces with angles > 5°
- Cylinder diameter > 0.3 mm
- Radii > 0.5 mm

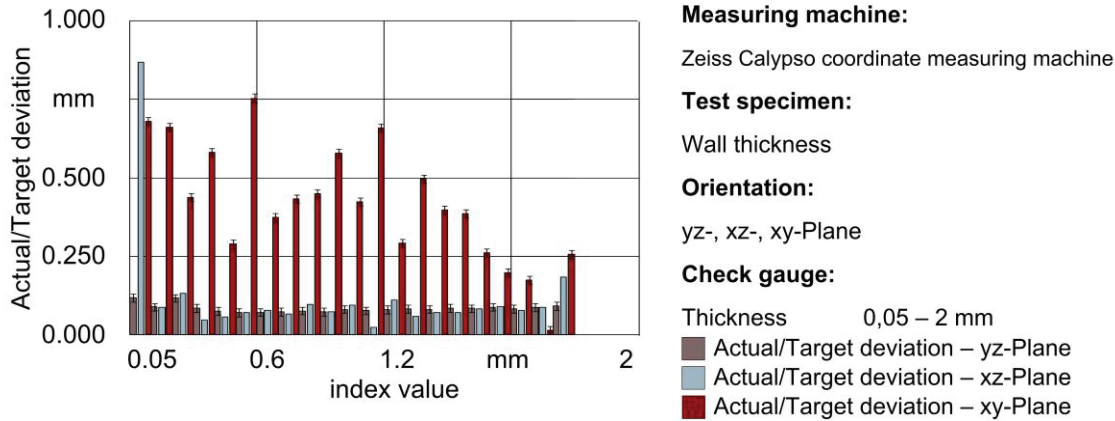


FIGURE 7. Measuring of wall thickness, XY-Plane shows critical orientation of coater and baseplate.

Method

The developed verification method of design rules for AM covers the whole value-chain from design to the quality management. It gives a feedback about the surface and geometric quality. In addition, an alternating implementation of the test structure can be used for continuously improvement of the design and subsequently the process quality of AM processes, systems and materials in general.

OUTLOOK

Different variances and improvements of the test component could be built with regard to specialized applications like horizontal holes or integration of support structures. Certain problems with optical and tactile measuring techniques lead to a need for research:

- Define a test structure to measure the accuracy of the shaping
- Validation of a suitable measurement method to cover the whole process-chain
- Implement a reference area to improve the measurements
- Cutting the baseplate could enhance measurement conditions

Although the process capability has increased in recent years, there are still some restrictions to the components design, like processing speed, post-processing treatment, limited choice of materials and their properties as well as others [3], [4]. In further development of AM processes the above named process-specific restrictions have to be evaluated to achieve a reliable process.

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AM design of a wafer conditioning table

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INTRODUCTION

In high-end manufacturing like semiconductor production, thermal control is a key enabler for high precision operations. Sub-micron machine positioning accuracy as well as product (substrate) stability is only possible under rigid control of the temperature. Part of the temperature control is done by liquid (mostly water) cooling channels at crucial locations.

Such cooling channels most often lead to manufacturing challenges. Also their shape and location often deviate from the optimum as a result of manufacturing constraints like wall thickness, seals, o-rings, heat affected zones, or large tolerances needed for brazing or welding. Also, liquid cooling solutions require many seals, hose couplings and manifolds. Each of which has a finite probability for failure, which leads to possible reliability issues.

By the use of metal additive manufacturing, these limitations of conventional cooling channels can be overcome. We will illustrate this for a wafer conditioning table manufactured in Aluminum using the Selective Laser Melting process.

WAFER TABLE REQUIREMENTS

Table 1 states the thermal and mechanical requirements for the table. As a result of the wafer contact, a very high cleanliness and surface quality is required.

To achieve good thermal contact to the wafer, currently two main solutions are used in the industry: a burl plate or an air bearing.

TABLE 1. Overview of typical requirements for a thermal wafer table

Wafer table size	300	mm
Flatness	<10	μm
Initial temperature deviation	1.2	K
Cooling time	10	s
Residual average wafer temperature	< 5	mK
Wafer temperature uniformity	<5	mK

Apart from the required flatness, the surface requirements for each of these solutions are very different. Within the current project, no concept choice has been made and the focus is on the water channel cooling performance and the manufacturability. Hence, no further requirements are stated for the wafer contact surface.

AM DESIGN CONSTRAINTS

Although providing a great freedom of design, metal AM is also constrained by limitations of the specific process that is used. For the current work, Selective Laser Melting (SLM) is used because of the ability to generate internal channels with small dimensions. The main characteristics of the SLM process that was currently used:

- Smallest feasible wall thickness and channel diameter: 1 and 2 mm, respectively in Al
- Geometrical limitations in channel design, 'overhang' structures and supports structures needed to facilitate successful printing (Figure 1, see [1] for an extensive overview).
- Building large horizontal planes often leads to stress in the material, this may be a problem for a wafer support table that needs to be very flat.
- The surface roughness/quality from the SLM process ($R_a \approx 5 \mu\text{m}$) is typically insufficient for critical surfaces, hence post-processing/machining is required (see also the paper presented by Goudsmit et.al. in this same meeting [8]).

DESIGN APPROACH

In general the design considerations for the conditioning table are:

- Maximize the surface of the water-metal interface
- Limit the pressure drop
- Maximize exchange by turbulence/vorticity
- Equal heat exchange over the entire plate surface area (Nusselt number)

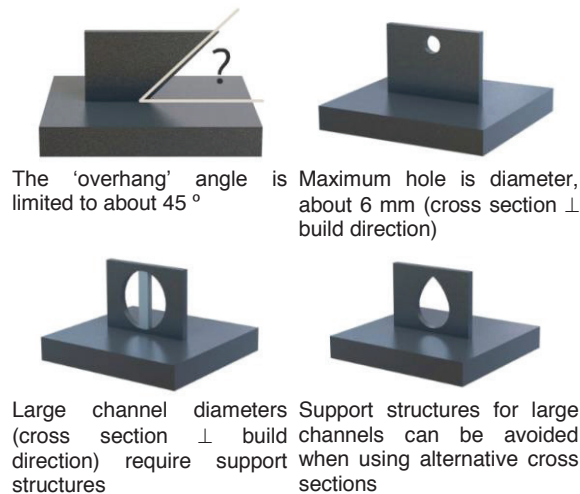


FIGURE 1 Selection of SLM design rules relevant for cooling channels, as published by the Ayre et. al. [1].

Based on these general design considerations, two starting points have been used for the design. One starting point was the classical approach using spiraling channels [see for instance [2-4]. In parallel, a design has been made with a pillar structure (pillars) as starting point [5-7].

This resulted in two 200 mm concept designs (Figure 1A & 1B) which were optimized, based upon thermal calculations and generic AM design rules [1]. The properties after optimization of the geometry are summarized in Table 2. Both designs cannot be realized using conventional technologies, give the thickness of the top plate and the wall thickness of the internal structures.

TABLE 2. Key parameters of both design approaches

Channels	
Height	1.5 mm
Width	4 mm
Length	1.2 m
Number	5
Flow regime	Turbulent
Pillars	
Pillar height	2 mm
Diameter of pillars	1.5 mm
Edge radius	2 mm
Number	400
Flow regime	Turbulent

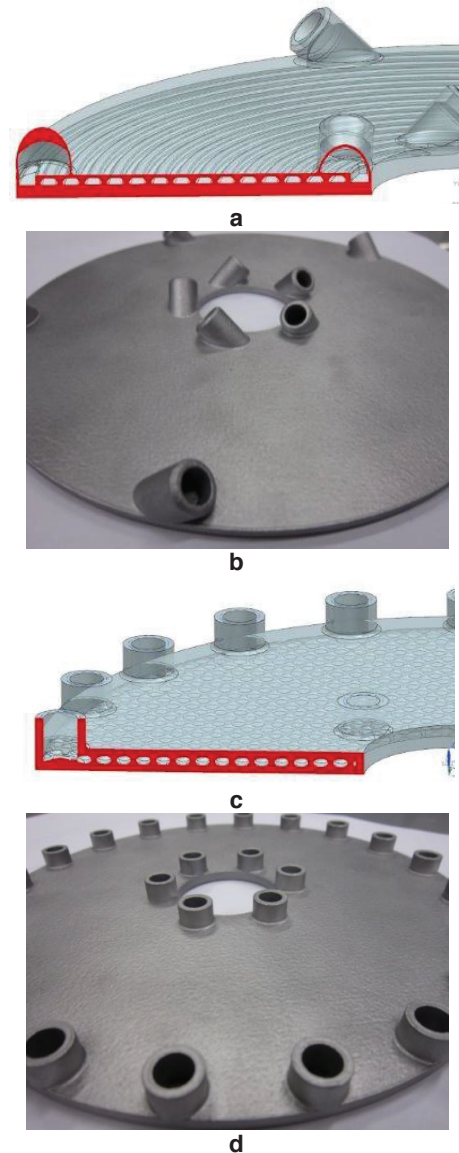


FIGURE 2. Drawings and test parts (200 mm) manufactured by SLM in AlSi10Mg of the channel concept a) & b) and the pillar concept c) & d).

SIMULATIONS

Both designs have been simulated for 300 mm table diameter. Residual temperature, uniformity and pressure drop have been evaluated. Pressure drop is important as the associated viscous losses generate heat that can be significant when going into the mK regime.

Preliminary analytical estimates showed that the thermal conductivity of Aluminum is needed to achieve the required performance, hence the full simulation was done using Aluminum as building material.

Channels

For the channel design, a straight channel has been modeled, using analytical estimates of the Nusselt and Reynolds number, which together determine the thermal transfer and water flow regime. The vertical transport is dominant over the lateral transport. Therefore, the results of the straight channel can be considered to be representative for the full table performance. As such, a pragmatic and efficient modeling approach was possible.

The modeling software was NX Flow. Turbulent effects were taken into account using a $k-\epsilon$ model, and assuming a surface roughness of 0.1 mm. The channel results are given in Figure 3. It can be seen that based on these simulations a residual temperature of 2.5 mK can be expected, where the temperature difference over the channel length is 5 mK and the pressure drop 590 Pa

It should be noted that in this approach the so called “local losses” are omitted, these are related to bends and corners in the flow. As a result, the calculated pressure drop will be slightly under-estimated, thus the residual temperature will be under-estimated as well. However, this was considered negligible.

For the full 300 mm table, 8 channels are needed that run in parallel, in nested spirals (see Figure 2a) with the flow from the inside to the outside of the wafer.

Pillars

For the pillar approach, there was little literature reference for the given structure. Especially, the determination of the Reynolds and Nusselt numbers was not possible based upon literature. Hence, a more elaborate full CFD approach using the same software as for the channels was chosen, as can be seen in Figure 4.

The results of the simulation (Figure 4) show that a residual temperature of 3 mK can be expected, where the maximum temperature difference over the cooling table is 6 mK. The according pressure drop was found to be 140 Pa.

Concluding, it can be stated that the simulations show that both designs are theoretically capable of meeting the required cooling performance. Both approaches seem to be capable of achieving the required conditioning down to a few mK at an acceptable pressure drop.

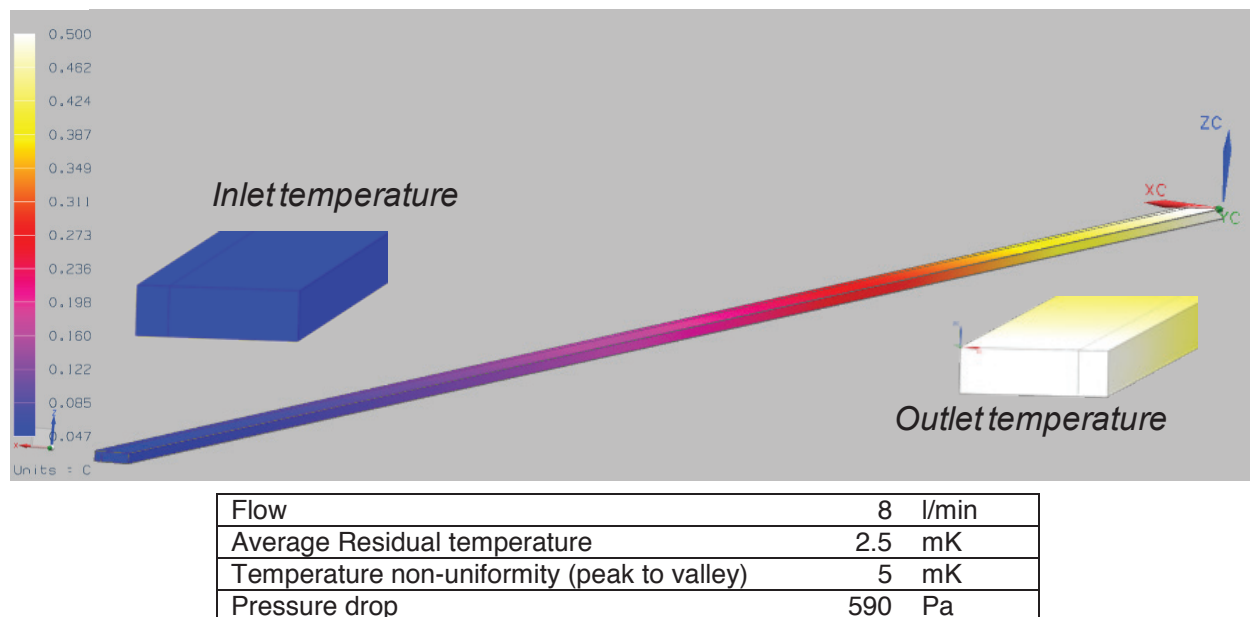
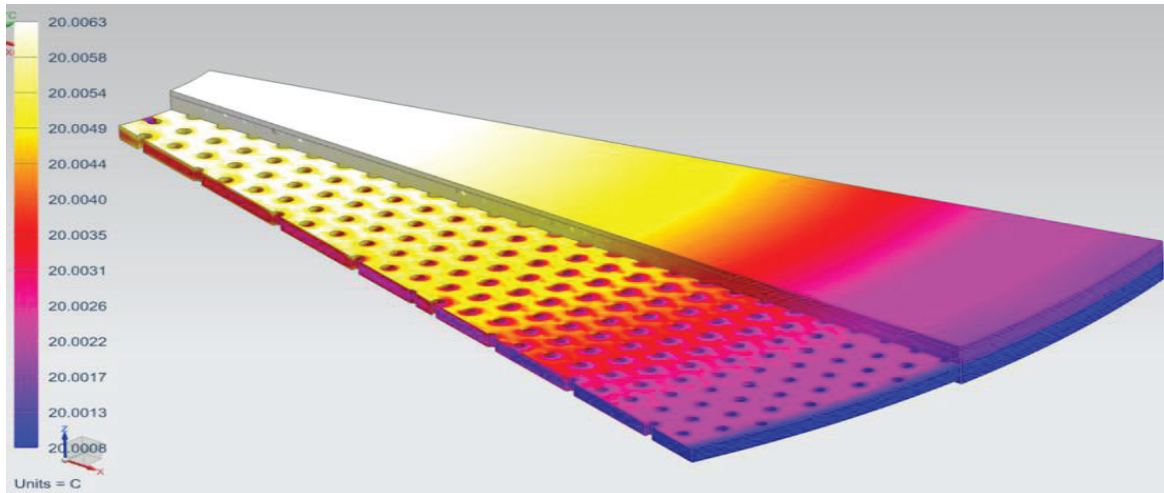


FIGURE 3 Overview of the modeling results for the channel design. A straight channel has been modeled, of which the full 300 mm table contains 12 pieces that are equally distributed. The simulated wafer temperature after 7 seconds is shown which was calculated for a flow of 8 l/min through the complete wafer table. Viscous and internal losses are omitted; hence a slight offset in residual temperature can be expected in reality.



Flow	10 l/min
Average Residual temperature	3 mK
Temperature non-uniformity (peak to valley)	6 mK
Pressure drop	140 Pa

FIGURE 4 Overview of the modeling results for the pillar design. A circular segment has been modeled, assuming a homogeneous inflow and outflow at the edges. The flow is from the outside to the inside. The figure and the table show the simulated wafer temperature after 7 seconds, at a flow of 10 l/min through the complete wafer table.

MANUFACTURING RESULTS

Based on these designs, concept test models have been designed to investigate the thermal performance and cleanliness, omitting flatness which is investigated in parallel using different samples [4]. Both models were manufactured using SLM of an Al10SiMg alloy (Figure 2), with a powder size distribution in the range of 20-40 μm .

The parts were build in a flat orientation, with the flat top surface facing downwards. The build process went without significant problems.

The concept test models showed good material properties and could be machined straightforward to assemble hose connections. The surface roughness Ra was 10-15 μm and the initial flatness of the table after the SLM process is 0.4 -0.8 mm.

CLEANING

After manufacturing, a cleaning sequence was applied to investigate the removal of particles from the internal channels (Table 3). During each step, the release of particles was measured and particles were analyzed qualitatively. The target of this experiment was to assess the feasibility of achieving fully particle

free internal channels. No full cleanliness qualification was done yet.

In general, the removal of particles was according to what can be expected. The wet cleaning with subsequent alkaline and etching solutions was essential for effective particle removal. Part of the particles consisted of conglomerates of molten particles with sizes well over the initial powder size (Figure 5), these clusters were only observed during the wet cleaning.

TABLE 3 Overview of the cleaning parameters

Cleaning method	Observations	
	Channel plate	Pillar plate
Dry cleaning with CDA and vibration <i>Particle counter</i>	Large amount of particles removed, mostly initial size distribution	Few particles removed
Wet alkaline cleaning <i>Filter analysis</i>	Few metallic clusters 62-106 μm Single particles 19 -37 μm	Few metallic clusters 60-194 μm Single particles 15-24 μm
Wet cleaning with etching solution <i>Filter analysis</i>	Metallic impurities, organic contaminants and soluble material was easily removed by chemicals	

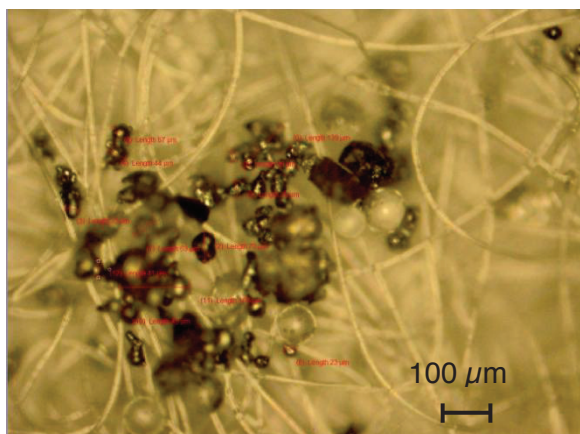


FIGURE 5 Microscope image showing large conglomerates of particles with diameters well over 50 μm , captured in a filter.

The results were sufficiently promising to consider cleanliness feasible.

THERMAL EXPERIMENTS

To verify the simulations and to compare both design alternatives, a measurement set-up has been designed. A well conditioned cooling water cabinet is used to supply cooling water with mK temperature stability. The top side of the cooling plates is covered with polyimide heaters and calibrated PT1000 temperature sensors (Figure 6).

Using a programmable power supply, the table is heated until a steady state temperature is reached. After that, the heater is switched off, the temperature response over time is measured. The average residual temperature as well as the spatial distribution over the table will be analyzed and compared to the simulations.

The thermal experiments are currently in progress. A preliminary result of the pillar design can be seen in Figure 7.

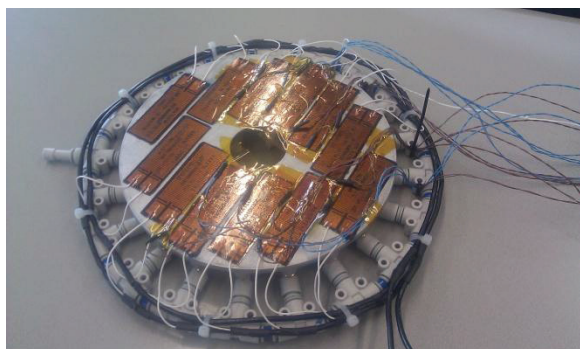


FIGURE 6 Overview of the pillar design table with heaters and sensors attached.

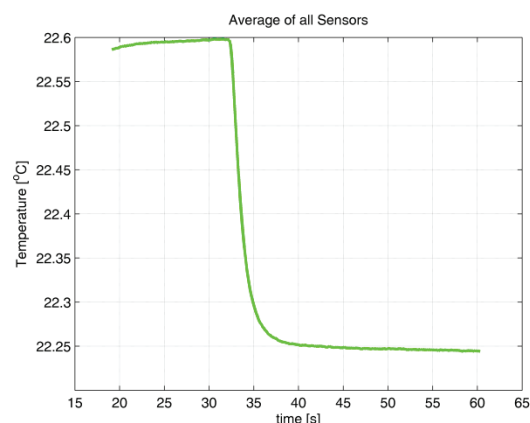


FIGURE 7 Temperature response curve measured using the thermal test set-up. Shown is the step response from a steady state deviation of about 0.45 $^{\circ}\text{C}$ back to the initial cooling water temperature of 22.25 $^{\circ}\text{C}$.

It can be seen that the average response is very fast and that the surface temperature of the thermal plate returns close to the initial value within 10 seconds. At this stage, no final conclusion on the residual temperature can be drawn, since a more detailed analysis is required, taking into account sensor characteristics, noise, drifts in the system etc. However, the response observed corresponds qualitatively to the simulated behavior and gives confidence that the envisioned improvement can be reached.

CONCLUSION & OUTLOOK

Summarizing, using AM can bring great value to high-end thermal conditioning units like the wafer table presented in the current paper.

Simulations show that it is possible to go beyond state-of-the-art cooling performance while at the same time eliminating failure modes of seals, interfaces and hose couplings.

Experimental tests look promising. However, full thermal verification and testing still has to be finalized to prove this performance.

Manufacturing was feasible for two different designs. So far, no manufacturing or cleanliness show-stoppers have been found for applying this technology in a high-tech environment.

The main concern when industrializing this technology is the material consistency and

residual stress after the SLM process, which both are required to achieve the accuracies and surface properties typical for high-tech applications. Hence, this should be the core for ongoing research.

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Extension of prior developed design rules' range of validity for different boundary conditions in laser sintering

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INTRODUCTION

Additive manufacturing technologies create plastic or metal parts layer by layer. Thereby, the manufacturing principle provides benefits that cannot be obtained with established manufacturing technologies. The extension of design freedoms is one of the most noteworthy benefits of additive manufacturing [1]. Consequently, highly complex parts can be manufactured that cannot be produced with conventional technologies like milling or casting.

However, additive manufacturing is still rarely industrial established for direct manufacturing purposes. Different limiting factors harm its establishment. One limiting factor is the insufficient availability of comprehensive design rules for additive manufacturing [2]. At time, such design rules are rarely available and technology specific [3].

Thus, within the research project "Direct Manufacturing Design Rules" [DMDR, 2010 – 2013] design rules were developed systematically for the additive manufacturing processes laser sintering (LS), laser melting (LM) and fused deposition modeling (FDM). Thereby, the same methodical proceeding was used for each considered process. This proceeding allows the comparison of technology specific design rules with each other and consequently the identification of design commonalities between the considered processes. From these commonalities many design rules could be deduced which apply for all considered processes.

AIM

Within the DMDR project design rules have been developed using static boundary conditions; the considered machines, materials and parameter settings were kept constant.

Thus, the developed design rules currently apply just for the boundary conditions considered within project. It is unknown in which way the material, the according parameter settings and the machine itself do influence the developed design rules. However, design rules for additive manufacturing technologies need to be applicable for different boundary conditions. Thus, the research project "Direct Manufacturing Design Rules 2.0" (DMDR 2.0, 2013 - 2016) has the aim to extend the range of validity for the developed design rules.

In order to extend the range of validity, the methodical proceeding of the DMDR project is used to repeat the experimental tests with different boundary conditions. Next, the results will be compared with the results from the DMDR project. Based on the comparison it will be analyzed if and how far the range of validity can be extended for the developed design rules. Within this paper the laser sintering process is in focus.

METHODICAL BACKGROUD

The bases for the design rule development are standard elements. These are geometrical elements which are often used to design technical parts. They are divided into three groups:

- Basic elements: Elementary geometrical shapes (e.g. cylinders, walls ...)
- Element transitions: Areas in which basic elements are combined with each other (e.g. joints)
- Aggregated structures: Arrangements of two or more basic elements and their transitions (e.g. overhangs, islands ...)

Each standard element has various belonging attributes; the thickness is an example for an

attribute of a plate. Due to the setting of the attribute values, shapes of standard elements can be concretized and varied.

Using standard elements, the design phase of technical parts is marked by an iterative proceeding of three main steps: selecting the required standard elements, setting the attribute values to concretize the elements' shapes and combining the elements with each other in order to create the part structure.

While designing technical parts a suitable design for manufacturing is always aspired. Means, design measures shall be used to assure the requirement-oriented compliance of manufacturing dependent quality aspects [4]. Using design measures, the quality of standard elements – and consequently of parts – can be directly influenced by varying the attribute values. Thus, design rules have to recommend ranges for attribute values that ensure the manufacturability of standard elements in a high quality.

In order to figure out those suitable ranges, standard elements can be manufactured with different attribute values. Furthermore the quality of the manufactured elements can be examined and related to the assigned attribute values. Based on the results design rules can be deduced [5, 6].

EXPERIMENTAL TESTS

Within the DMDR project, design rules for laser sintering were developed using an Eosint P395 machine with the material PA2200 and the parameter setting PPP120 (table 1; BC_1.1). The results from the DMDR project provide the reference data which the measurement data of the DMDR 2.0 project will be compared with.

Within the DMDR 2.0 project, up to now three additional boundary conditions were considered (table 1). In BC_2.1 and BC_2.2, the parameter-set was changed to PPP60 and PPP180. In order to test a different material, the boundary condition BC_2.3 considers PA3200GF with the belonging parameter-set PPP150.

In order to extend the design rules' range of validity, standard elements were manufactured with different attribute values for each boundary condition. Per every boundary condition and attribute value standard elements were

manufactured three times. Next, this proceeding will exemplarily be presented for three attributes.

TABLE 1. Considered boundary conditions

Boundary condition	Parameter	
BC_1.1	Machine:	Eosint P395
	Material:	PA2200
	Parameter-set:	PPP120
	Layer thickness:	0.120 mm
BC_2.1	Machine:	Eosint P395
	Material:	PA2200
	Parameter-set:	PPP60
	Layer thickness:	0.060 mm
BC_2.2	Machine:	Eosint P395
	Material:	PA2200
	Parameter-set:	PPP180
	Layer thickness:	0.180 mm
BC_2.3	Machine:	Eosint P395
	Material:	PA3200GF
	Parameter-set:	PPP150
	Layer thickness:	0.150 mm

Walls: Thickness

For the examination of suitable wall thicknesses, cuboids were used as test specimens (figure 1). The orientation was varied between $\delta_0 = 0^\circ$ and $\delta_0 = 90^\circ$. Per orientation the thickness was varied in 13 steps from 0.20 mm to 5.0 mm. The length and the width were set to 10.0 mm.

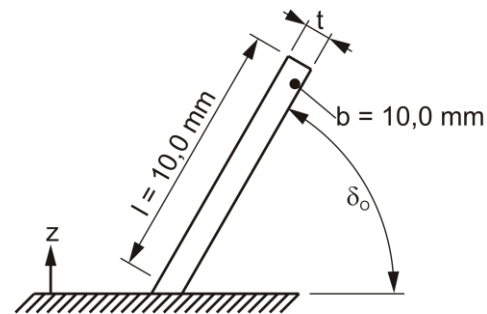


FIGURE 1. Test specimen for the examination of suitable thicknesses for walls.

In order to examine the quality of the test specimens, the thickness was measured with a micrometer. From the results the dimensional deviation was calculated by subtracting the nominal thickness from the measured thickness. Figure 2 shows both the reference data from DMDR project (BC_1.1) and the test data from the DMDR 2.0 project (BC_2.x).

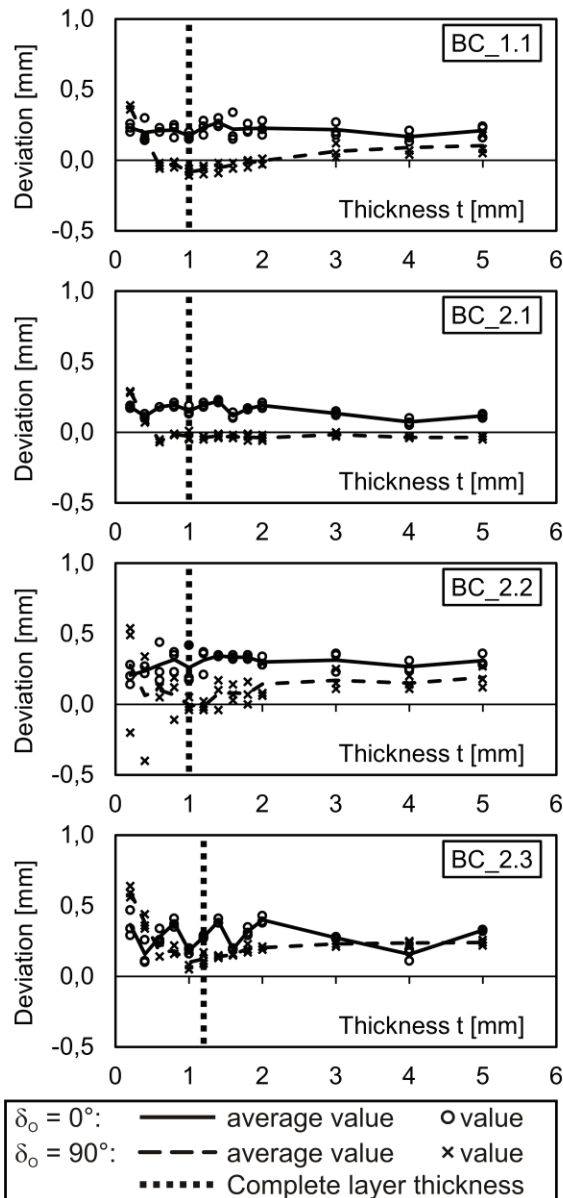


FIGURE 2. Dimensional deviations of the measured thicknesses versus the nominal thickness.

The test data show a similar behavior as the reference data. In an orientation of $\delta_o = 0^\circ$, oversizes occur. Independently from the nominal thickness the values remain nearly constant. For a small layer thickness of 0,60 mm (BC_2.1) the oversize value is about 0,2 mm. Larger layer thicknesses lead to enlarged oversize values up to 0,4 mm. Considering $\delta_o = 90^\circ$ orientations, large dimensional deviations and data variances occur for small nominal thicknesses. These become small and behave stabile once the nominal thickness reaches a certain value.

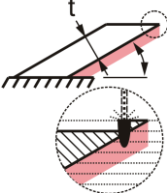
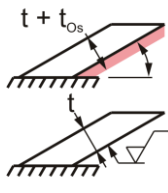
Within the DMDR project, it has been found that the oversize occurs in $\delta_o = 0^\circ$ orientations due to the melting bath that the laser generates inside the powder. This penetrates deeper than through one layer in order to bond the currently manufactured part layer to the part layer below. However, while creating the first part layer, there is no part below. Thus, the melting bath bonds particles to the part layer that don't belong to the part [6,7]. Generally, the energy per area that the laser conducts into the powder is higher for larger layer thicknesses. This leads to larger melting bath dimensions and consequently to increased oversizes.

As well, it is known from the DMDR project that the dimensional deviations of $\delta_o = 90^\circ$ oriented walls become small and behave stabile once the nominal thickness is large enough to build each part layer with contour lines and enclosed raster lines (dashed line in figure 2). Contour lines limit the extensions of part layers in x-y-direction and raster lines fill the space in-between. This is the complete part layer structure that the additive manufacturing processes laser sintering, laser melting and fused deposition modeling always aspire. To create complete part layer structures the wall thickness has to provide the required space. Otherwise, dimensional deviations occur [6, 7]. Obviously, the test data shows the same behavior like the reference data. Therefore, the design rules from the DMDR project are valid for the considered boundary conditions, too (table 2, 3).

TABLE 2. Design rule for wall thicknesses

Wall thicknesses should be large enough to structure each layer with a contour line and enclosed raster lines to minimize dimensional deviations and to avoid defects.	
<u>Laser sintering:</u> BC_1.1: $t \geq 1,0$ mm BC_2.1: $t \geq 1,0$ mm BC_2.2: $t \geq 1,0$ mm BC_2.3: $t \geq 1,2$ mm	<u>Laser melting:</u> $t \geq 0,6$ mm <u>FDM:</u> $t \geq 1,5$ mm
Unsuitable design 	Suitable design

TABLE 3. Design rule for wall thicknesses

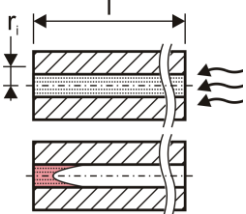
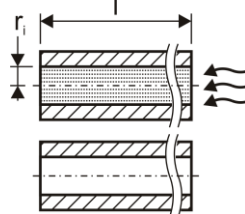
Wall thicknesses should be large enough to structure each layer with a contour line and enclosed raster lines to minimize dimensional deviations and to avoid defects.	
<u>Laser sintering:</u> BC_1.1: $t_{Os} \geq 0,2$ mm BC_2.1: $t_{Os} \geq 0,2$ mm BC_2.2: $t_{Os} \geq 0,4$ mm BC_2.3: $t_{Os} \geq 0,4$ mm	<u>Laser melting:</u> $t_{Os} \geq 1,5$ mm <u>FDM:</u> /
Unsuitable design 	Suitable design 

Bores: Length related to the inner radius

In order to examine the length of a bore related to its inner radius, hollow cylinders were used as test specimens. Their length was set to $l = 200$ mm, their inner radius was varied with $r_i = 0,5 / 1,0 \dots 2,5 / 5,0 / 7,5 / 10,0$ mm and the wall thickness was set to $t = 2,0$ mm.

After manufacturing, the powder was removed from the insides of the test specimens by glass bead blasting (4 bars). In the next step a calliper was used to measure the length inside the bore that was free from powder. Figure 3 shows both the reference data from DMDR project (BC_1.1) and the test data from the DMDR 2.0 project (BC_2.x).

TABLE 4. Design rule for the length of a bore [7]

Bores' lengths should be short enough to enable a robust removal of powder materials from its insides.	
<u>Laser sintering:</u> BC_1.1: $l \leq 10 * r_i$ BC_2.1: $l \leq 10 * r_i$ BC_2.2: $l \leq 10 * r_i$ BC_2.3: $l \leq 8 * r_i$	<u>Laser melting:</u> $l \leq 400 * r_i$ <u>FDM:</u> /
Unsuitable design 	Suitable design 

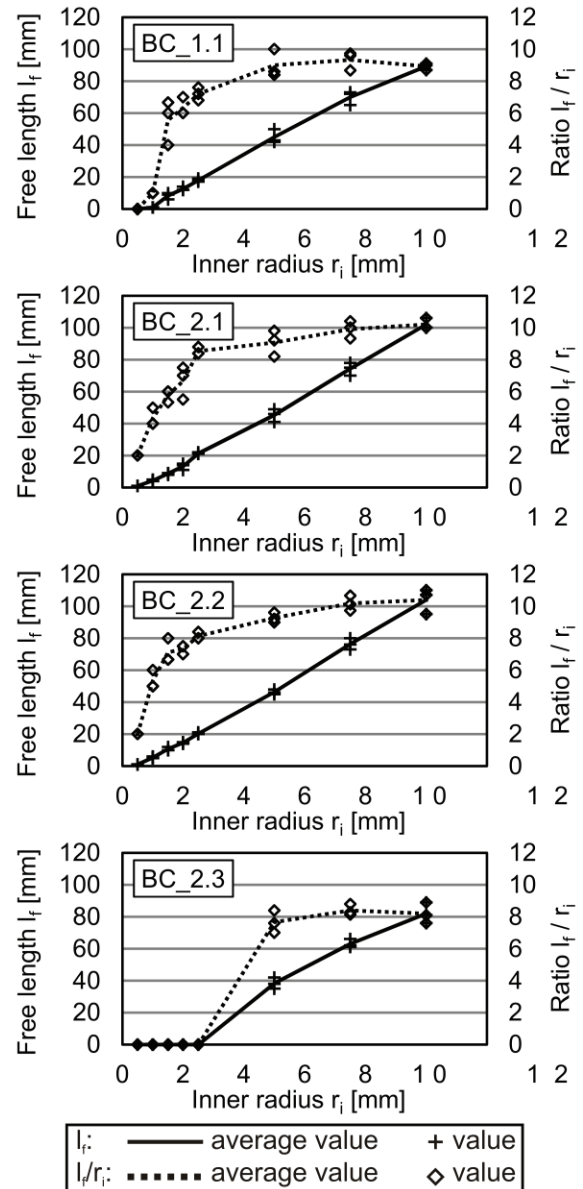


FIGURE 3. Bores free length l_f and l_f/r_i ratio versus the nominal inner radius r_i

All results show an almost linear correlation between the free length l_f and the nominal inner radius. As well, all l_f/r_i ratios trend to values between 8 and 10 for large inner radii. From the results of the DMDR project the design rule shown in table 4 was deduced for the length of a bore related to its inner radius [7]. The comparison of the measured data shows that, the design rule is valid for the additionally considered boundary conditions, too.

Non-bonded element transitions: Gap height

Additive manufacturing offers the potential to create transitions between non-bonded

geometrical elements. Using these, form fittings can be manufactured directly together with the form fitted elements itself. Therefore, gaps are required between the combined elements [8].

In order to examine suitable heights for gaps, the test specimen shown in figure 4 was considered. The gap height was varied with $h_g = 0,05 / 0,10 / 0,15 / 0,20 / 0,30 \dots 1,0$ mm.

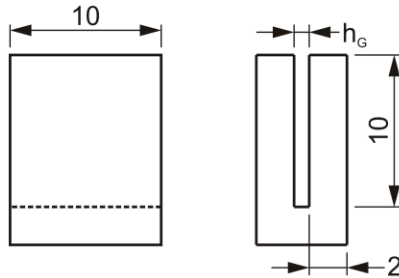


FIGURE 4. Test specimen for the examination of suitable gap heights.

After manufacturing, the test specimens were cleaned from powder using glass bead blasting. Next, the gap height was measured with a feeler gauge. Figure 4 shows the reference data (BC_1.1) and the test data (BC_2.x).

For all measurement values applies that gaps are sealed if the nominal gap height is small [8]. However, the value from which on the gaps are free from powder is layer thickness dependent. Small layer thicknesses lead to small values for free gaps: for instance gaps were free for $h_g \geq 0,1$ mm if the layer thickness was 0,06 mm and for $h_g \geq 0,8$ mm if the layer thickness was 0,18 mm.

Once the gaps are free from powder, the averaged measurement values stay stable relative to the reference value [8]. The smaller the layer thickness becomes the smaller the deviation value is. For layer thicknesses of 0,06 mm and 0,12 mm the deviation tends to zero. For layer thicknesses of 0,15 mm and 0,18 mm the deviation is $\approx 0,3$ mm.

The larger the layer thickness becomes the higher is the energy per area that the laser conducts into the powder. Consequently, the size of the melting bath and coevally, the heat affected zone increases. Thus, for large layer thicknesses the gap height has to be larger in order to avoid gap sealings due to powder, which adheres to the gap shaping surfaces. As well, larger heat affected zones increase the

amount of powder that adheres onto the surfaces. Consequently, the deviation value increases with larger layer thicknesses.

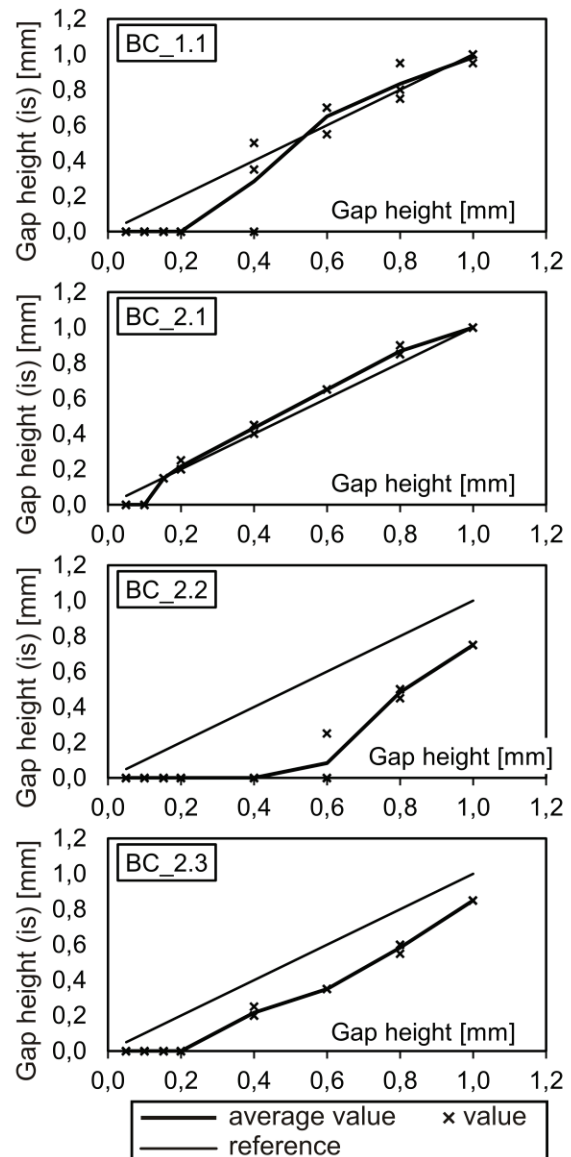
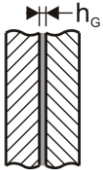
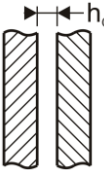


FIGURE 5. Measured gap heights versus nominal gap heights.

The general description of the design rule developed within the DMDR project fits for the additionally considered boundary conditions (table 5). However, the reference data and the test data show different behaviors for different boundary conditions. These differences are marked by numerical values that are presented for the considered boundary conditions within the special description of the design rules.

TABLE 5. Design rule for the height of a gap

Minimal gap heights should be kept in order to ensure a robust manufacturability of unsealed gaps	
<u>Laser sintering:</u> BC_1.1: $h_G \geq 0,6$ mm BC_2.1: $h_G \geq 0,2$ mm BC_2.2: $h_G \geq 0,8$ mm BC_2.3: $h_G \geq 0,4$ mm	<u>Laser melting:</u> $h_G \geq 0,2$ mm <u>FDM:</u> $h_G \geq 0,4$ mm
Unsuitable design 	Suitable design 

SUMMARY AND CONCLUSION

In principle, a proper design for manufacturing is the required prerequisite for a robustly manufacturable part design. Thus, within the DMDR project many design rules were developed that support a sufficient design for additive manufacturing. Of course, the design rules were only valid for the considered boundary conditions which were used for the design rule development.

In order to extend the validity of the design rules, the DMDR 2.0 project has the aim to prove if the design rules are applicable for a broader range of boundary conditions. Therefore various parameter sets, materials and machines are considered. First results of experimental tests performed with laser sintering show direct commonalities to the reference data from the DMDR project. The measured values behave comparable. Thus, in most cases the general descriptions of the design rules are applicable for different boundary conditions. However, different parameter sets and materials can lead to different numerical values for which the general descriptions become valid. In order to point out these differences, the concrete numerical values are stated within the boundary specific descriptions of the design rules. Together, both descriptions provide the information that is required to design parts that shall be manufactured with certain boundary conditions.

Although the presented results indicate that the design rules are valid for different boundary conditions, further tests are required. These

need to consider different machines. To get information about the influence of the machine type, a test job has been developed that will be manufactured by different suppliers. As well different boundary conditions for further processes like laser melting and fused deposition modeling need to be explored. These tests will be performed within the further proceeding of the DMDR 2.0 project.

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Evaluation of the effect of defects on the mechanical performance of components manufactured by selective laser melting

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ABSTRACT

The current paper focuses on the selective laser melting (SLM) process and the role of internal features on the mechanical performance of components manufactured by this additive manufacturing (AM) technique.

In order to thoroughly investigate the impact of process induced defects on the mechanical performance, different metallic materials, e.g. stainless steel 316L and titanium alloy Ti-6Al-4V, were processed by SLM and subsequently subjected to diverse loading conditions. Defects which have been considered within this study are internal stresses, micron-sized pores and unsuitable evolution of the microstructure due to high cooling rates present in the SLM-process.

The results obtained show that each material is affected in a specific way by the processing parameters employed for SLM. A thorough characterization of the resulting microstructure, immediately after the SLM-process and after different post-treatments, allowed for deducing the damage mechanisms for each material.

Titanium alloy Ti-6Al-4V in the as-built condition is mainly characterized by its highly brittle behavior due to an unfavorable microstructural evolution and high residual stresses. Besides the monotonic behavior, especially the high-cycle-fatigue performance suffers from process-induced defects. Micron-sized pores act as strong stress raisers and lead to premature fatigue crack initiation. In this case, appropriate post-treatments are necessary in order to obtain a performance similar to the behavior of Ti-6Al-4V manufactured by conventional processes.

In contrast, stainless steel 316L does not undergo a phase-transformation during cooling

and is characterized by a considerably higher ductility. The effect of residual stresses is not severely pronounced. These aspects lead to a more balanced behavior under monotonic loading as well as a lower sensitivity regarding premature crack initiation under cyclic loading. In consequence, stainless steel 316L seems to be suitable for producing near-net-shape components without the requirement for applying any post-treatments in terms of stress-relieving and microstructure manipulation in general.

Hence, based on internal defects of SLM processed materials, the damage mechanisms found lead to different optimization strategies for both materials. Thus, different kind of post-treatments and their influence on the mechanical performance were evaluated on basis of the resulting microstructural interactions.

Therefore, microstructural evolution has been investigated by use of electron backscatter diffraction (EBSD) and X-ray diffraction (XRD) measurements. In addition, high resolution computed tomography (CT) scans allowed for obtaining a precise picture regarding size and distribution of pores.

Predictive modeling capabilities for dimensional accuracy and surface finish in Metal Laser Melting based Additive Manufacturing

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OVERVIEW

The dimensional accuracy and surface finish of parts created using metal melting based additive manufacturing (AM) technologies are a function of the resolution of the energy source, geometry of the desired part, orientation of the part during the build, material, process parameters and their coupled interactions. The resolution of the energy source is generally of the order of $\sim 10^{-2}$ to 10^{-3} times less than part feature dimensions in metal laser powder bed AM. If the accuracy required is greater than the beam diameter ($\sim 10^{-4}$ m), achieving that accuracy does not pose a significant challenge. However, if higher accuracies are required then excellent control of laser position and scan strategy are required.

Unlike for powder bed fusion based AM, the resolution of the energy sources in most directed energy deposition processes, such as a SCIAKY wire-fed electron beam system, pose accuracy problems since the beam diameters are much larger ($\sim 10^{-2}$ m) and the accuracy required may be a small fraction of the beam diameter.

Yet another source of inaccuracies in part dimensions occurs due to the stair stepping effect induced as a result of transformation of a 3D solid model into 2D slices for fabrication. This effect can be minimized by performing careful calculations and optimization of the build orientation, leading to a smoother texture on desired surfaces along with better control and tailored use of thinner layers, if possible. However, some of the remedies such as a smaller beam size and thinner layers are counter-productive in terms of build times.

The additive manufacturing research group at the University of Louisville is beginning to apply its multi-scale AM modeling infrastructure to the problem of prediction of dimensional accuracy and surface finish in metal AM processes. The long term objective of this study is to optimize and control the process based upon easy-to-

implement strategies for reducing dimensional inaccuracies and surface finish variations which do not have any adverse effect on the efficiencies of production.

Better control of AM processes requires fast and accurate simulations. This is particularly difficult for laser based AM since the cause-effect relationships are non-linear and therefore require evaluation of the full-factorial process-parameter space and material variable space (a time-consuming simulation that, due to its difficulty, has not been frequently used for furthering machine development to date).

Over the past 4 years a comprehensive set of modeling tools have been developed at the University of Louisville for quickly and accurately predicting the effects of changes in process parameters on mechanical properties, residual stress/strain, crystal structure, and other micro & macro features of components made using metal-based additive manufacturing (AM) techniques [1-8]. This research has resulted in the development of multi-scale, multi-physics finite element solvers that have been shown to be many orders of magnitude faster than commercially available tools while achieving comparable or better solution accuracy.

In continuation of our past efforts in simulation and modeling, two new simulation modules are being developed to focus on the areas of surface finish and dimensional inaccuracy. The first module is based on the prediction of geometrically non-linear solidification shrinkage and residual stress development leading to overall change in dimensions of the part. The second module is based on the computation of runtime melt pool geometry as a function of process parameters and local part geometry to identify non-symmetrical thermal profiles and surface deviations from the desired geometry during scanning of the part boundaries. Experiments are being conducted to verify and

validate the predictive capabilities of these modules. The status of these efforts will be discussed in this talk.

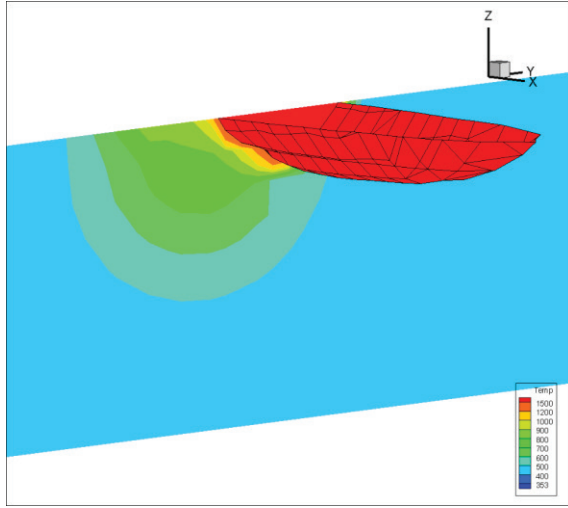


Figure 1: Stainless Steel melt pool and asymmetric thermal contours at the edge of a part being built. These thermal contours are diffused in the solidified portion of the bed (where an adjoining laser scan has already resulted in a solid region of the layer) and restricted on the powder side.

EXPERIMENTAL PLAN

Samples for this study were fabricated using a Metal Laser Sintering machine (EOS M270). The samples were fabricated using a martensitic precipitation hardening stainless steel with 17% Chromium and 4% Nickel (abbreviated 17-4 PH) powder. The processing parameters were laser power of 195 W, scan speed of 800mm/s, layer thickness of 20 μm , hatch spacing of 100 μm and an assumed beam diameter of 100 μm (with the beam expander set at a value of 2). It is known that the beam diameter changes with the set value of the beam expander but it is not understood how much variation in the beam diameter occurs as a result of beam expansion which is a scale between 0-9 in the standard EOS M270 machines and is considered a vendor's secret. This parameter set is the default setting for 17-4 PH powder in an EOS M270 machine.

In order to ease distortion measurements, a novel canonical geometry has been conceptualized, designed and fabricated. The advantages of this design include dimensional measurements at only a few locations compared to the entire part, manifestation of distortion and thermal behavior as a function of designed part curvatures and surface roughness as a function of curvature since thermal profiles are asymmetric at the part edges where the solid part comes in direct contact with the powder. The design of the part

and the initial conceptualization are shown in Figure 2 and Figure 3 respectively.

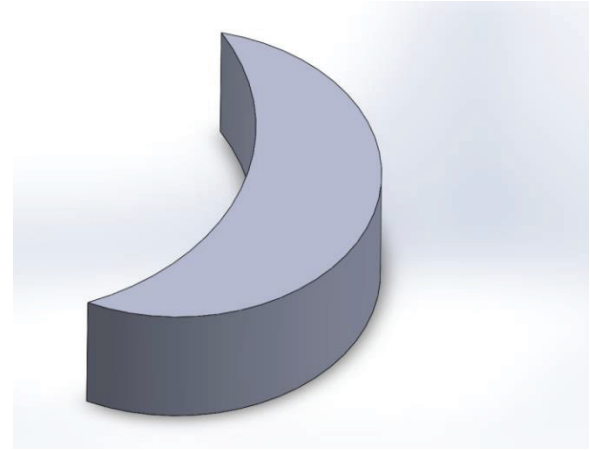


Figure 2: Designed part

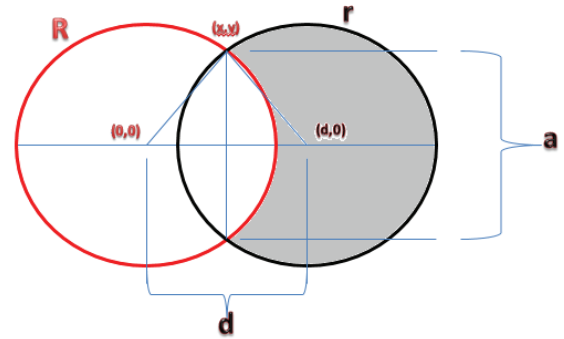


Figure 3: Initial conceptualization of the part with circle of radius R (red) subtracted from the circle of radius r (black) leading to the shaded part creation.

Two sets of samples were fabricated based upon this design. The first set used an equal radii for both circles but a different offset 'd' between the circle centers. This set was designed such that all samples had equal area but four different offsets (d) and radii. The calculation for the area of the part was accomplished by first calculating the area of the lens between the red and black circles using equation (1)

$$\text{Area of lens} = R^2 \cos^{-1} \left(\frac{d^2 - r^2 + R^2}{2dR} \right) + r^2 \cos^{-1} \left(\frac{d^2 + r^2 - R^2}{2dr} \right) - \frac{1}{2} \sqrt{4d^2 R^2 - (d^2 - r^2 + R^2)^2} \quad (1)$$

Since for this set of samples the radii of both the circles are the same, the area of the lens becomes a function of offset distance 'd' and radius R as shown in equation (2).

$$\text{Area of lens} = 2R^2 \cos^{-1} \left(\frac{d}{2R} \right) - \frac{1}{2} d \sqrt{4R^2 - d^2} \quad (2)$$

For computing the part area, the area of the lens is deducted from the circular area of radius 'R' as shown in equation (3).

$$\text{Part area} = \pi R^2 - 2R^2 \cos^{-1} \left(\frac{d}{2R} \right) + \frac{1}{2} d \sqrt{4R^2 - d^2} \quad (3)$$

The sample sets with their geometry variables are listed in Table 1.

Table 1: Equal area different diameter and offset samples

Diameter (mm)	Offset, d (mm)	Lens Area (mm ²)	Crescent Area(mm ²)
50	10	1466.849	495.651
40	12.62	760.349	495.651
30	17.60	210.849	495.651
60	8.31	2330.349	495.651

In Figure 4, the layout of the samples in the EOS machine has been illustrated. Three replicates of each sample set (Table 1) have been accommodated in the build envelope to capture statistical variations in distortion and surface roughness during the measurements. The three replicates were inclined at 45°, 90° and 0° with respect to the x-y reference axis.

Similarly, a second set of samples has been fabricated with a radius of 40 mm across the sample sets but with different curvatures. The definition of curvature has been mathematically represented using equation (4).

$$x^n + y^n = r^n \quad (4)$$

where n denotes the curvature (1, 2, 3 and 4) of the inner bounding curve.

The effect of curvature on designed bounding curves is shown in Figure 5.

Three replicates for each curvature and the build layout are shown in Figure 6.

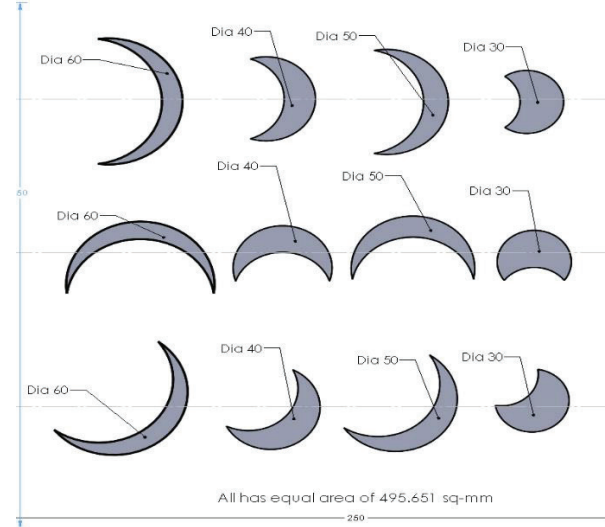


Figure 4: Equal area different diameter and offset sample sets. This figure illustrates the layout of the samples to be fabricated in the EOS machine.

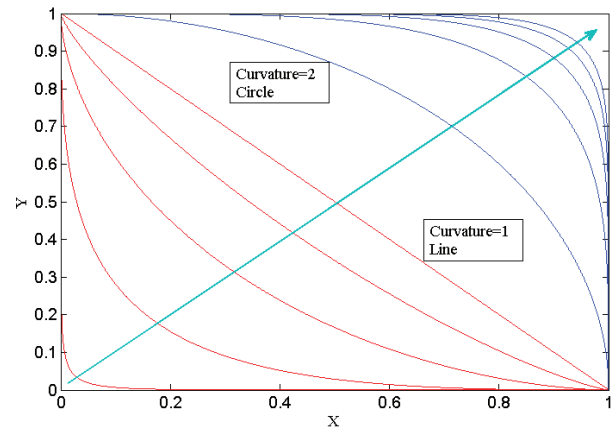


Figure 5: Bounding curve as a function of curvature

RESULTS AND DISCUSSION

The experimental plan has been executed and images of the as-built parts still attached to the baseplate using support structures are shown in Figure 7 and Figure 8. Figure 7 corresponds to the Figure 4 (set1) layout and Figure 8 corresponds to the Figure 6 (set 2) layout respectively.

Measurements on the as-built samples were performed twice, the first time measurements were conducted before the samples were sheared from the base plate followed by another set of measurements after the samples were sheared off the base plate. The measurements were required after shearing from the base plate

in order to gauge the effect of elastic recovery due to residual stress.

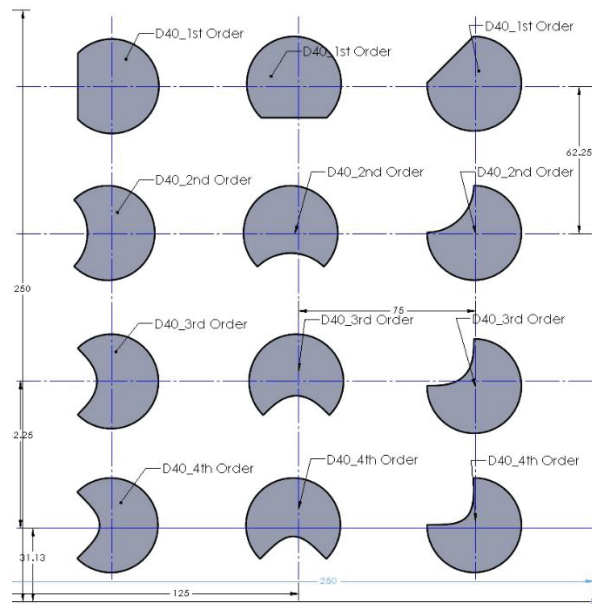


Figure 6: Equal diameter with different curvatures associated with the inner bounding curves.

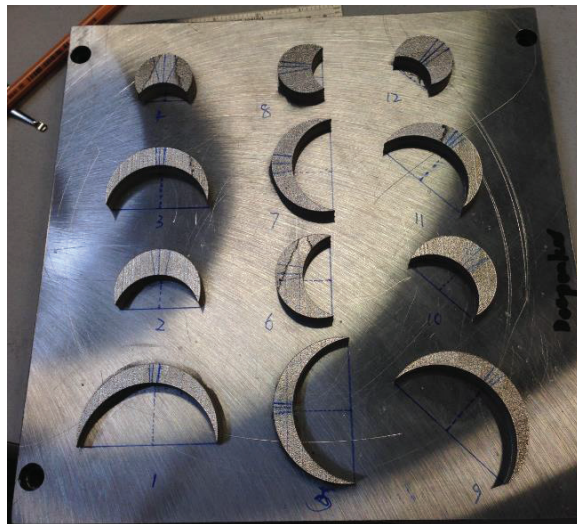


Figure 7: Different diameter equal area (Set 1) samples

The measurement strategy on these samples has been shown in Figure 9. The measurement strategy includes labeling 3 adjacent lines according to the midcourt line of the two tip points and using the longest one to represent the thickness and using the sharp edges to measure the open jaw dimensions of the sample.

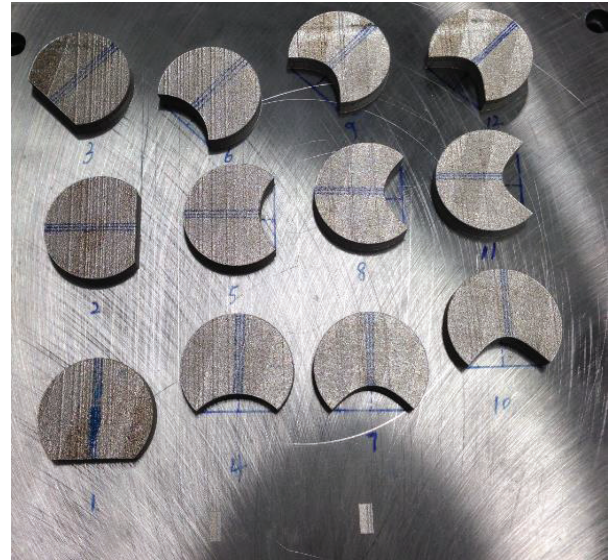


Figure 8: Constant radius, but different order inner bounding curve (Set 2 samples).

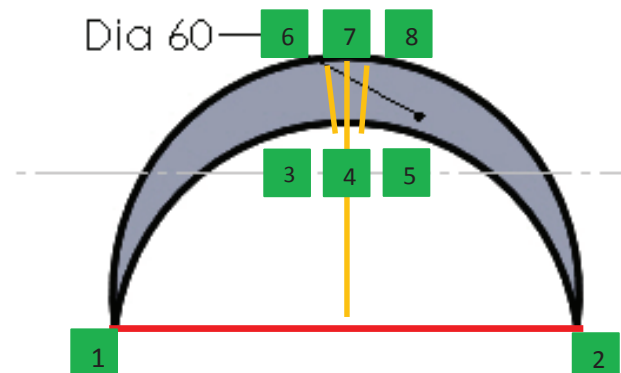


Figure 9: Schematic explaining how the Crescent measurement was carried out.

A total of 8 points per sample have been measured for each crescent with Digital Calipers with an accuracy of 0.001mm according to the scheme shown in Figure 9.

The results of open jaw (opening dimension) measurements and the thickness measurements for set 1 are tabulated in Table 2 and Table 3 respectively.

Table 2: Open jaw dimension measurements before and after shearing the samples off the supports and contrast w.r.t. to the designed model values (Sample set 1). The measurement was between points 1 and 2 of Figure 9. The tabular values are organized as a function of decreasing bounding curve diameter. In this table, the open jaw measurements are tabulated as a function of the bounding curve diameters 60mm, 50mm, 40 mm and 30 mm respectively.

Model value (mm)	Before Cutting (mm)	After Cutting from the base plate (mm)	Variation from model (before cutting) (mm)	Variation from model (after cutting) (mm)	Variation Elastic recovery residual stress + Rand. Error (mm)
59.42	59.95	59.81	0.53	0.39	-0.14
59.42	59.96	59.93	0.54	0.51	-0.03
59.42	59.98	60.01	0.56	0.59	0.03
48.99	49.3	49.30	0.31	0.31	0.00
48.99	49.3	49.32	0.31	0.33	0.02
48.99	49.32	49.32	0.33	0.33	0.00
37.96	38.43	38.40	0.47	0.44	-0.03
37.96	38.42	38.40	0.46	0.44	-0.02
37.96	38.42	38.39	0.46	0.43	-0.03
24.29	24.42	24.41	0.13	0.12	-0.01
24.29	24.42	24.40	0.13	0.11	-0.02
24.29	24.42	24.42	0.13	0.13	0.00

From Table 2 and Table 3, it is clear that the variations in the open jaw dimensions are higher than the thickness variations when compared to the designed dimensions. Another interesting fact is that the elastic recovery during the shearing off of the samples from the substrate (cutting the support structure) is minimal and was not shown to be statistically significant.

Table 3: Thickness dimension measurements before and after shearing the samples off the supports and comparison to the designed model values (Sample Set 1). Model thickness was taken as the widest dimension when measuring between points 3&6, 4&7, and 5&8 as shown in Figure 9. In this table, the thickness measurements are tabulated as a function of the bounding curve diameters 60mm, 50mm, 40 mm and 30 mm respectively.

Model thickness (mm)	Before Cutting (mm)	After Cutting (mm)	Variation from model (before cutting) (mm)	Variation from model (after cutting) (mm)	Variation due to residual stress + Rand. Error (mm)
8.31	8.34	8.34	0.03	0.03	0.00
8.31	8.34	8.34	0.03	0.03	0.00

8.31	8.34	8.33	0.03	0.02	-0.01
10	10.1	10.07	0.1	0.07	-0.03
10	10.15	10.07	0.15	0.07	-0.08
10	10.1	10.07	0.1	0.07	-0.03
12.62	12.73	12.72	0.11	0.10	-0.01
12.62	12.73	12.72	0.11	0.10	-0.01
12.62	12.72	12.73	0.1	0.11	0.01
17.6	17.73	17.73	0.13	0.13	0.00
17.6	17.75	17.71	0.15	0.11	-0.04
17.6	17.74	17.72	0.14	0.12	-0.02

For sample set 2, the results of both open jaw (opening dimension) measurements and the thickness measurements have been tabulated in Table 4 and Table 5 respectively.

Table 4: Open jaw dimension measurements before and after shearing the samples off the supports in comparison with the designed model values (Sample Set 2). The colors in this table represent the open jaw measurements corresponding to 1st order, 2nd order, 3rd order and 4th order inner bounding curves.

Model opening (mm)	Before Cutting (mm)	After Cutting (mm)	Variation from model (mm)	Variation from model (after cutting) (mm)	Variation due to residual stress + Rand. Error (mm)
27.85	28.08	28.05	0.23	0.20	-0.03
27.85	28.09	28.07	0.24	0.22	-0.02
27.85	28.08	28.06	0.23	0.21	-0.02
28.07	28.34	28.37	0.27	0.30	0.03
28.07	28.34	28.35	0.27	0.28	0.01
28.07	28.34	28.34	0.27	0.27	0.00
28.07	28.34	28.34	0.27	0.27	0.00
28.07	28.34	28.33	0.27	0.26	-0.01
28.07	28.34	28.34	0.27	0.27	0.00
28.07	28.34	28.35	0.27	0.28	0.01
28.07	28.34	28.34	0.27	0.27	0.00
28.07	28.34	28.35	0.27	0.28	0.01

Again the variations in the open jaw measurements with respect to the designed dimensions are higher than their thickness counterparts. Another interesting observation is that the variation in opening dimension remained the same irrespective of the curvature of the inner bounding curve. As mentioned earlier, the inner bounding curves have been provided with higher curvatures in order to obtain different surface roughness on the inner bounding curved plane.

The surface roughness is still under investigation and will be reported soon.

Table 5: Thickness dimension measurements before and after shearing the samples off the supports in comparison with the designed model values (Sample Set 2). The colors in this table represent the open jaw measurements corresponding to 1st order, 2nd order, 3rd order and 4th order inner bounding curves.

Model thickness	Before Cutting	After Cutting	Variation from model	Variation from model (after cutting)	Variation due to residual stress + Rand. Error
34.36	34.45	34.45	0.09	0.09	0.00
34.36	34.45	34.41	0.09	0.05	-0.04
34.36	34.45	34.41	0.09	0.05	-0.04
28.5	28.54	28.54	0.04	0.04	0.00
28.5	28.55	28.53	0.05	0.03	-0.02
28.5	28.55	28.54	0.05	0.04	-0.01
26.05	26.72	26.13	0.67	0.08	-0.59
26.05	26.13	26.15	0.08	0.10	0.02
26.05	26.15	26.14	0.1	0.09	-0.01
24.72	24.81	24.79	0.09	0.07	-0.02
24.72	24.79	24.77	0.07	0.05	-0.02
24.72	24.82	24.78	0.1	0.06	-0.04

A simulation is being run the laser scan pattern shown in Figure 10.

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WORK IN PROGRESS

1. Full part metrology using optical techniques so that human measurement errors can be minimized.
2. Investigation of surface roughness.
3. Full simulation using scan patterns matching the geometry of the part. This laser scan pattern is being solved using patent pending thermomechanical solver algorithms.

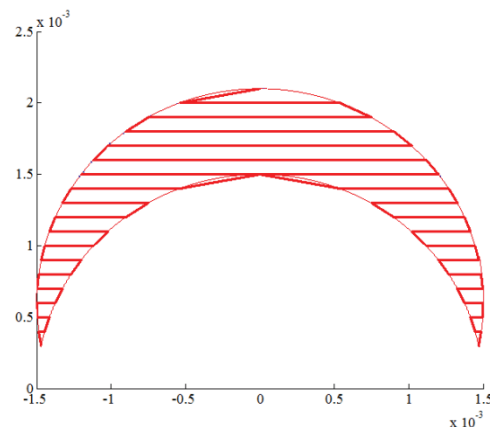


Figure 10: Programmed scan pattern with fill and contour of the part designs mentioned above.

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Estimation of Surface Roughness of Additive Manufacturing Parts Using Finite Difference Method

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ABSTRACT

By extension of the range of applications of the Additive Manufacturing (AM) products their surface roughness is becoming an importance factor. In order to have an exact evaluation of roughness in AM parts, it is essential to have a proper and accurate sense Representation of Surface Integrity over the AM surface. Surface Integrity Representation (SIR) requires acquisition of numerous points of the part's geometry from different regions of the model, it applies extra cost and time during the procedure. This paper provides a novel approach to estimate the distribution of geometric deviation based on limited number of measured points. Therefore, an exchange between time and cost regarding to an acceptable accuracy is offered. By employing the finite difference method a new approach is developed to reconstruct the surface geometry using sample measured data. The preciseness of this method is studied on actual rapid prototyped parts. The developed methodology can also be used in inspection of rapid prototyping parts for the purpose of process control, experimental study of the effect of process parameters on the surface quality, and to plan for appropriate upstream manufacturing process after the additive manufacturing process.

METHODOLOGY

A second order partial differential equation, which is often in two dimensions written as:

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0 \quad (1)$$

is called Laplace equation. If Laplace equation is solved over a boundary condition, function f which satisfies both the Laplace equation and its boundary conditions, is called a harmonic function. Harmonic functions possess unique properties which are of interest to the developed methodology [4].

In order to estimate the detailed deviation zone conformal mapping method using a harmonic function with Dirichlet boundary problem is used. In the current approach, instead of assuming a single shape centre with the potential value of zero, we consider a group of shape sites and their deviation attributes as the potential function to run the Finite Difference Iteration. This way the deviation attributes for the empty nodes between the shape sites are computed. In order to implement this concept the Laplace equation over the grid is solved. The numerical solution for Laplace equation can be obtained using Taylor's series neglecting higher order terms [3]:

$$\frac{\partial^2 f}{\partial x^2} = \frac{\phi(x_{i+1}, y_i) - 2\phi(x_i, y_i) + \phi(x_{i-1}, y_i)}{h^2} \quad (2)$$

$$\frac{\partial^2 f}{\partial y^2} = \frac{\phi(x_i, y_{i+1}) - 2\phi(x_i, y_i) + \phi(x_i, y_{i-1})}{k^2} \quad (3)$$

Where h and k are the grid step sizes along u and v coordinates respectively, and Φ is the detailed deviation zone function. Considering equal step sizes in x and y directions, Finite Different Method formula can be extracted as:

$$\phi(x_i, y_i) = \frac{1}{4} [\phi(x_i, y_{i+1}) + \phi(x_{i+1}, y_i) + \phi(x_i, y_{i-1}) + \phi(x_{i-1}, y_i)] \quad (4)$$

To initiate the iteration another equation is defined as follow, where j is the iteration index:

$$\phi_{j+1}(x_i, y_i) = \frac{1}{4} [\phi_j(x_i, y_{i+1}) + \phi_j(x_{i+1}, y_i) + \phi_j(x_i, y_{i-1}) + \phi_j(x_{i-1}, y_i)] \quad (5)$$

CASE STUDY

As a case study, a rapid prototyped industrial model with dimensions of 50mm × 70mm was considered (Figure 1). Measurement process was conducted. Through this process a grid with

size of 1155x1537 was created and 1,775,235 points were captured for the estimation process.

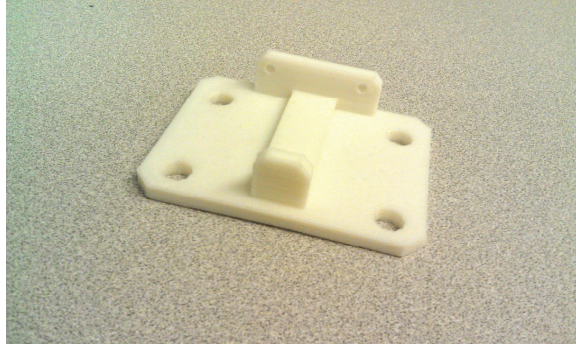


FIGURE 1. The Rapid Prototyping Part Produced by 3D Printing.

A number of 177,524 of these points which is 10% of all the points were selected randomly and were used to form the grid, when the rest of the grid node values were replaced with zeros. Considering the typical points accuracy between 10^{-7} (mm) and 10^{-9} (mm), a threshold of 10^{-12} (mm) is selected to terminate the iteration process. As it can be seen in Figure 2 and Figure 3, after 500 iteration runs the grid is evolving to find the rest of the nodes based on the available sites. The values of the site points remains fixed during the iteration process.

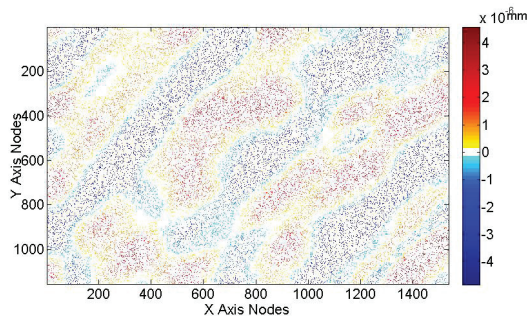


FIGURE 2. Discrete Measured Points distribution before iteration runs.

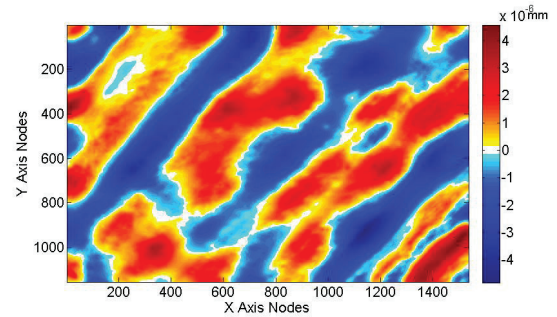


FIGURE 3. Surface Integrity Representation after 500 runs.

After the estimation process is finished, the roughness of the surface can be calculated using the arithmetic average of absolute values formula:

$$R_a = \frac{1}{n} \sum_{i=1}^n |e_i| \quad (6)$$

Where n is the number of all the points and e_i is the deviation estimated in the previous step.

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THE INFLUENCE OF HEAT ACCUMULATION ON THE SURFACE ROUGHNESS IN ADDITIVE MANUFACTURING BY ELECTRON BEAM MELTING® (EBM)

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ABSTRACT

The influence of heat accumulation on the surface roughness of Ti-6Al-4V plates has been investigated. For this purpose, a series of plates with 100 mm × 100 mm × 1 mm in dimensions were produced by electron beam melting® (EBM). Three different spacing distances including 5 mm, 10 mm, and 20 mm were used, while heat input used for producing all samples was identical. Even though the thermal conductivity of loose powder is much lower than that of solidified Ti-6Al-4V, it was found that during the cooling step, the area under high temperature in a setup with minimum spacing distance was very large. According to the experimental measurements of surface roughness, the arithmetic mean height (Sa) values of 68 µm, 56 µm, and 49.6 µm were measured for the spacing distances of 5 mm, 10 mm, and 20 mm, respectively. The increased amount of heat accumulated at a sample with minimum spacing distance caused the partial melting of powder particles, which resulted in a higher surface roughness. An equation was derived from experimental data to predict the values of surface roughness as a function of spacing distance.

Keywords: Additive Manufacturing, Electron Beam Melting® (EBM), Spacing Distance, Heat Accumulation, Surface Roughness

INTRODUCTION

The ability of additive manufacturing (AM) processes in producing almost any complex design resulted in a very rapid growth of this technology. However, there are still some limitations that have to be addressed. Considerable surface roughness could be an inherent characteristic of AM processes with powder bed system. It is shown that in some applications such as biomedical implant industry, presence of a controlled level of surface roughness is beneficial [1]. Ponader et al. [2] studied the surface roughness of Ti-6Al-

4V as an effective parameter on attachment, proliferation, and differentiation of human fetal osteoblasts (hFOB). The Ti-6Al-4V samples were manufactured by EBM® process. It was shown that samples with limited surface roughness ($R_a < 24.9 \mu\text{m}$) were best suited for cell proliferation, while on samples with higher surface roughness ($R_a > 56.9 \mu\text{m}$) proliferation of hFOB cells was reduced. Thomsen et al. [3] studied the effect of surface roughness on the bone-to-metal contact in an implant produced by EBM®. Results showed that higher level of surface roughness resulted in a greater absolute contact between bone and implant, which may improve biomechanical behavior of the implant, as well. However, excessive surface roughness will provide surface area for potentially adverse effects such as crevices of microorganisms as well as ion release.

Poor surface finish is not desirable in many applications. It is reported that surface roughness caused by un-melted powders has been the possible reason for crack initiation in non-stochastic lattice structures produced by EBM® [4, 5]. In any additive manufacturing process, a 3D CAD model is sliced into number of thin layers. These thin or 2D layers are stacked on top of each other in order to create the 3D object, while presence of geometric gaps between CAD model and printed object is almost inevitable. These differences are known as stair-stepping effect [3]. Therefore, one source of the surface roughness is the design. It is shown that stair-stepping effect is more pronounced on inclined surfaces [3]. Moreover, because a thinner layer thickness can be set by using smaller powder particles, the size of powder particles has a remarkable influence of surface roughness. Using smaller powder particles minimizes the stair-stepping effect [6]. Also, it is reported that surface roughness can be different at downward-facing and upward-facing surfaces with a given inclination angle. Bacchewar et al. [7] showed that the downward-facing surface has a higher average surface

roughness. This difference can be explained by considering the filleting effect observed on downward-facing surfaces.

Numerical modeling could be a good tool to investigate the influence of different parameters on properties of parts produced by additive manufacturing. So far, some numerical models have been developed to provide a better understanding of physical phenomena occurring during EBM®. Jamshidinia et al. [8, 9] investigated the influence of fluid convection as well as process parameters on temperature distribution at EBM®. Also, a coupled CFD-FEM model was developed to study the effects of EBM® process parameters on residual stress [10]. Moreover, a structural model was developed to optimize the design of a dental abutment produced by EBM® [11, 12]. Also, Ahn et al. [13] developed a model for the prediction of surface roughness in parts produced by Stereolithography (SL). The experimental data obtained by surface roughness measurement for different inclination angles was interpolated and an equation was developed for the prediction of surface roughness. Strano et al. [14] developed a mathematical model to study the effect of sloping angle on surface roughness of stainless steel 316L produced by Selective Laser Melting (SLM). It was shown that partial melting of powder particles around the molten pool has a considerable influence on roughness. Therefore, any parameter that affects the amount of heat available for partial melting could influence surface roughness. Some studies have investigated the effects of heat input on surface roughness. Safdar et al. [15] showed that an increase in heat input caused by increasing the beam current or decreasing either the beam scanning speed or offset focus, resulted in a higher level of surface roughness in Ti-6Al-4V parts produced by EBM®.

Even though some experimental and numerical modeling works have been performed to study the effects of different parameters on surface roughness, the effect of heat accumulation adjacent to the component surface, on its surface roughness is not thoroughly investigated, yet. While according to authors' observations, surface roughness of components produced by EBM® is considerably affected by the arrangement of components at the buildup plate inside the vacuum chamber. In this study, a mathematical model is developed to investigate the influence of components arrangement on heat accumulation and consequently on surface roughness. The

resultant surface roughness is measured experimentally. Also, an equation was derived from experimental data to predict the values of surface roughness as a function of spacing distances.

EXPERIMENTAL SETUP

Electron Beam Melting® (EBM)

Any 3D CAD model can be sliced into a number of layers and saved in .stl format. Electrons are produced by heating a tungsten filament and then accelerated by using a high voltage potential applied between the anode and cathode. The kinetic energy of electrons is transformed into heat upon striking the target material. The electron beam fully melts the powder where a solid is needed and partially where a solid is not needed. In post processing, the partially sintered powder is broken away in a powder recycling unit. More detailed information on EBM® process can be found in [8, 9]. In this study, a series of 100 mm× 100 mm× 1 mm thin plates, made of Ti-6Al-4V were produced by using three different spacing distances including 5 mm, 10 mm, and 20 mm (Fig. 1). All samples were produced by using the voltage, current, and scanning speed of 60 kV, 10 mA, and 100 mm/s, respectively.

Numerical Modeling

In this study, the temperature distribution during manufacturing of two thin plates is numerically investigated by using ANSYS. A domain with 1 mm height and 5 mm length is designed while three different widths including 5 mm, 10 mm, and 20 mm are used. Because of symmetry and in order to save in calculation time, only half of the 1 mm-plate width is considered for modeling. Therefore, the domain contains two traces with 3 mm length, 0.5 mm width, and 1 mm depth at the left and right sides, while the area in

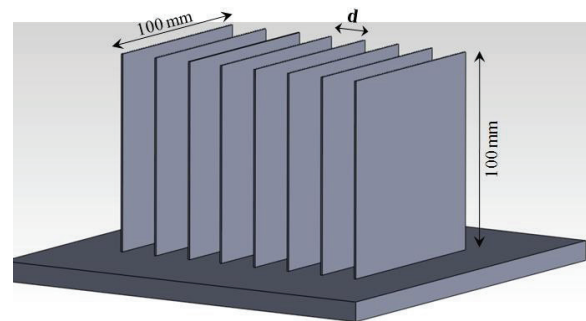


Figure 1. The schematic of plates' arrangement in EBM® building chamber; d is the spacing distance between plates.

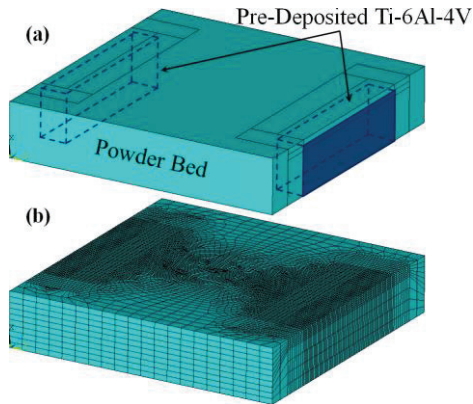


Figure 2. The schematic of domain geometry (a) and meshing (b) for spacing distance of 5 mm; the blue surface and dotted lines show the pre-deposited Ti-6Al-4V.

between two traces is filled by loose powder (Fig. 2-a). The blue surface and dotted lines show the pre-deposited Ti-6Al-4V. A uniform temperature of 973 K is applied on the whole domain as the initial condition. Also, temperature dependent properties of Ti-6Al-4V in solid and powder forms are used [8]. In order to improve the model accuracy, the properties of loose powder are assigned to the top layer of thin wall with 0.1 mm thickness. However, by scanning with the electron beam, the corresponding elements properties change to those of solidified Ti-6Al-4V. The tetragonal elements are used for meshing the domains (Fig. 2-b). In order to avoid inaccuracy caused by poor meshing, the mesh independency test was performed. Figure 3 plots the maximum temperatures in the molten pool achieved by using different numbers (sizes) of elements for the spacing distance of 5 mm. According to the results, element sizes of 0.04 mm, 0.08 mm, and 0.25 mm were used for meshing the thin plates, plates' surrounding powders, and rest of the powder bed area, respectively.

Roughness Measurement

The surface roughness of thin plates was measured by using a 2-axis Nanovea PS50 profilometer, equipped with a 400 μm optical pen, providing a 1.3 μm lateral resolution with a vertical accuracy of 136 nm. The scanning direction was set along the building direction of plates, while the dual frequency mode was activated for the range of 30 Hz to 200 Hz. Also, the scanning steps were set equal 1 μm and 4 μm , along and normal to scanning direction.

RESULTS AND DISCUSSION

Numerical analysis showed that during the melting step, the spacing distance has no considerable effect on the temperature distribution and almost the same temperature profiles were achieved at different spacing distances. Figure 4 shows the temperature distribution in the domain with 5 mm spacing distance. The similarity of temperature distributions could be explained by the fact that melting step occurred very fast (0.03 seconds). Therefore, in such a short interaction time, heat transfer through powder bed with a low thermal conductivity has the minimal influence on temperature distribution. Figure 5 shows the temperature profiles at the time of 2.2 seconds of cooling step, from both top and bottom views. As could be seen, an increase in the spacing distance was accompanied by a decrease in the size of the area with high temperature in the domain. The difference in temperature distribution during the cooling step is more pronounced on the side view. It is shown that by increasing the spacing distance, the area

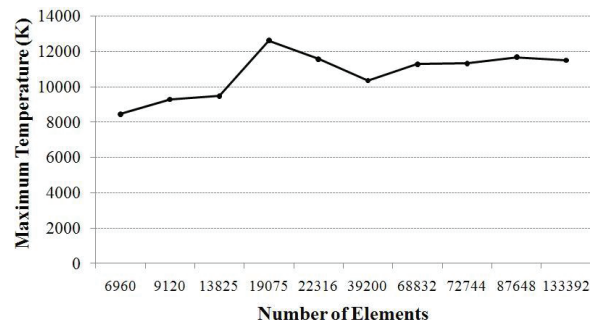


Figure 3. The influence of mesh size on the maximum temperature in melt pool at the domain with 5 mm spacing distance (a very high absorption coefficient is used).

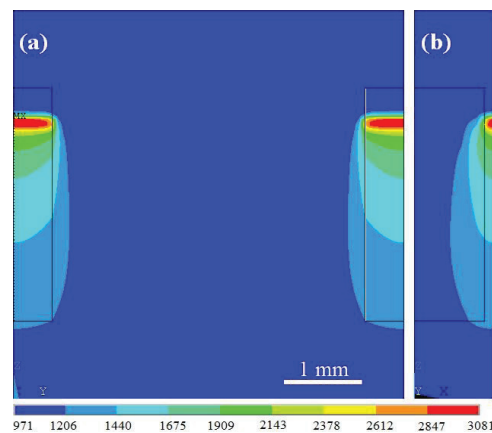


Figure 4. Temperature distribution during melting at the sample with 5 mm spacing distance; a) Top view, b) Side view.

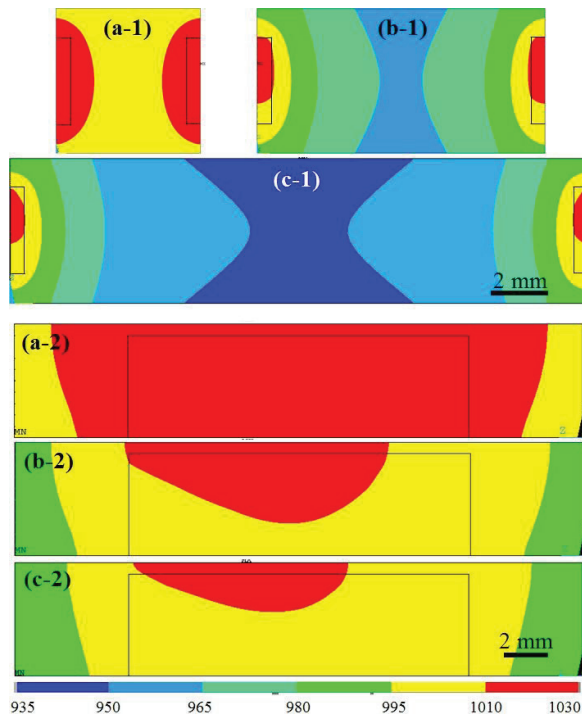


Figure 5. The comparison of temperature distribution during cooling at samples with different spacing distances of a) 5 mm, b) 10 mm, and c) 20 mm; 1) top view, 2) Side view

with high temperature shrinks and gets limited to shallower depth. It means that at samples with a longer spacing distance, less amount of heat is accumulated after the melting step. Therefore, the chance of partial melting and attachment of loose powder to solidified thin plate has an opposite relationship to the spacing distance.

Figure 6 compares the results of measured surface roughness on an area of 1 mm × 5 mm. As could be seen, the variation of surface height at a sample with 5 mm spacing distance is high, and almost all different colors corresponding to surface heights are repeatedly seen along the building direction. While, an increase in the spacing distance, resulted in minimizing the variation in height which could be interpreted as decrease in the surface roughness. The comparison of depth histograms corresponding to the three samples is presented in Fig. 7. As it is shown, by increasing the spacing distance, the peak of depth is shifted to smaller values or shallower depths. It means the sample with longer spacing distance has a smoother surface. Figure 8 plotted the measured values of Arithmetic Mean Height (S_a) for the three different samples. As it is expected, an increase in the size of spacing distance was

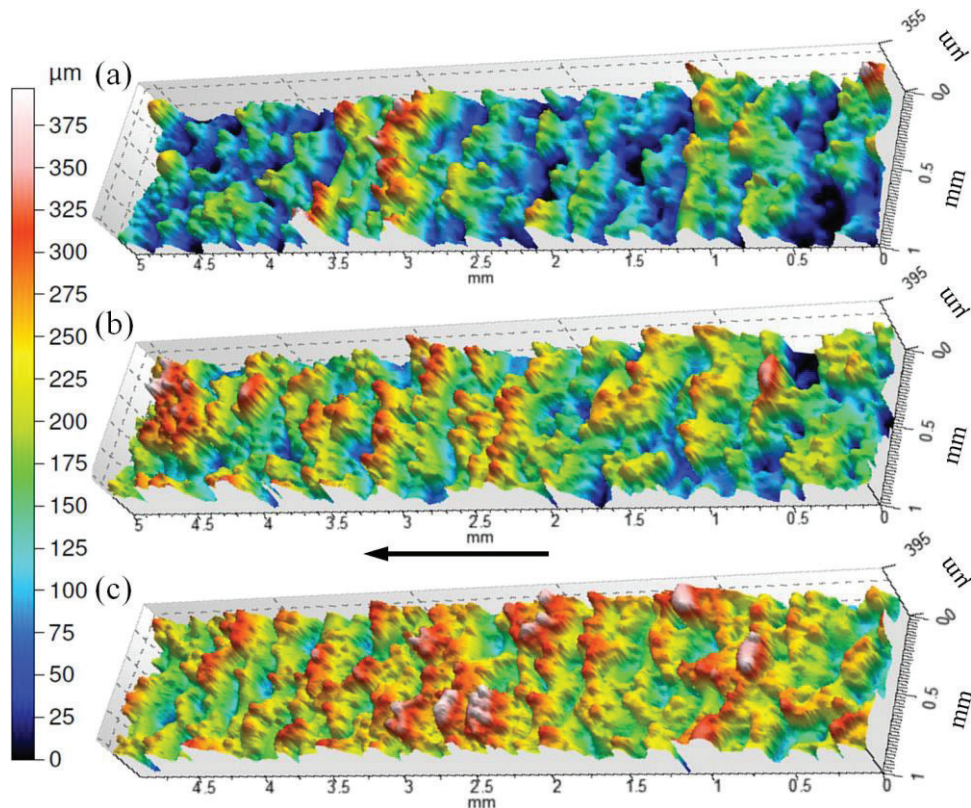


Figure 6. 3D representation of surface roughness at samples with different spacing distances of a) 5 mm, b) 10 mm, c) 20 mm; the black arrow shows the building direction of plates at EBM®.

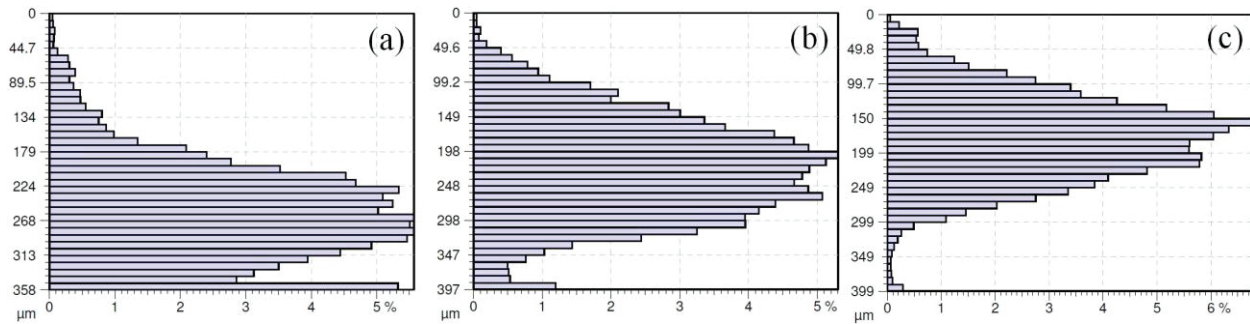


Figure 7. The comparison of depth histogram for different spacing distances including a) 5 mm, b) 10 mm, and c) 20 mm.

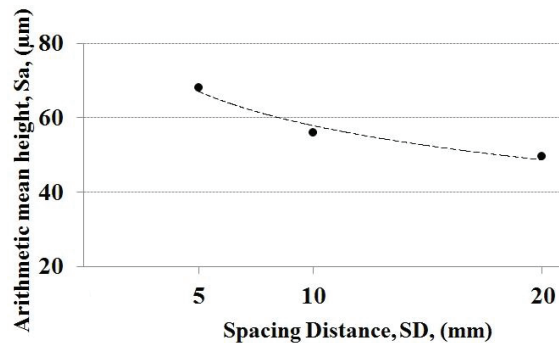


Figure 8. The influence of spacing distance (SD) on the arithmetic mean height (Sa).

accompanied by the decrease in surface roughness. According to the results of temperature distribution during cooling, the amount of heat accumulated around the solidified design has an opposite relationship to the spacing distance between thin plates. Therefore, by increasing the spacing distance, the probability of partially melted powder is decreasing. Consequently, the level of surface roughness improved. A logarithmic regression equation was established measured surface roughness (Eq. 1):

$$S_a = -13.24 \times \ln(SD) + 88.428 \quad \text{Eq. 1}$$

where, S_a is the arithmetic mean height in μm and SD is the spacing distance in mm. This equation could be used to predict the surface roughness of parts with the spacing distances between 5 mm to 20 mm. The spacing distance could be set by the arrangement of different components in the building chamber or between different sections of a single component.

CONCLUSIONS

In this study, the influence of heat accumulation during the layer-based manufacturing on the surface roughness was investigated. For this purpose, a series of thin plates with 1 mm thickness were produced by EBM® process,

while three levels of spacing distances including 5 mm, 10 mm, and 20 mm were selected. According to the obtained results, the following could be concluded:

- The temperature distribution during the melting step was almost identical for all three different spacing distances. This could be due to the very short interaction time between the electron beam and powder during the melting step as well as the low thermal conductivity of loose powder.
- The influence of spacing distance on the temperature distribution was more obvious during cooling step. In the case of minimum spacing distance, the area with higher temperature was much larger than in the case with maximum spacing distance. This difference could be explained by considering the larger volume of heat sink available at a sample with maximum spacing distance.
- Experimental results revealed an inverse relationship between the spacing distance and surface roughness, which is in accordance with numerical results. Higher amount of heat accumulated in a sample with shorter spacing distance, increases the chance of partial melting of powder and its attachment to the solidified surfaces.
- A logarithmic regression equation was established from the measured surface roughness. This equation could be used to predict the surface roughness of parts as a function of spacing distance.

FUTURE STUDY

In the future study, the numerical model will be developed to investigate the influence of multi-layered deposition of Ti-6Al-4V on heat accumulation during EBM®.

ACKNOWLEDGMENT

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Typical requirements for precision mechanical parts and opportunities for additive manufacturing

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INTRODUCTION

As high tech equipment evolves over time, system requirements become increasingly demanding. These requirements are for example processing speed or throughput, accuracy and repeatability of handling and positioning. These system level requirements lead to the need for better control of thermal uniformity, better structural dynamics, high cleanliness grades and vacuum compatibility. These evolving needs put a strain on the design and manufacturability of high-tech parts and assemblies.

With the recent proliferation of Additive Manufacturing (AM) for metal materials using powder bed fusion, new possibilities may arise to address some of the challenges for high tech parts and assemblies. AM offers the opportunity to put material where it is required from a performance perspective, as opposed to conventional manufacturing techniques that impose more constraints.

VDL ETG is a high-tech contract supplier of capital intensive equipment for clients active in very demanding manufacturing branches, such as: semiconductor, solar, analytical instruments, LED and health care. To complement the scientific academic publications we made a practical driven estimation on the possibilities of AM, using our experience in high tech volume production.

This paper presents an initial assessment on the opportunities for AM, starting from the perspective of functional specifications followed by the requirements on dimensional accuracy and surface conditioning that are typical for high-tech metal parts.

SPECIFICATIONS FOR HIGH TECH PARTS

For the assessment of the manufacturing requirements we first made an inventory of typical functional specifications for high tech

parts often manufactured by VDL ETG. We investigated three typical functional areas for high tech parts:

1. Thermal conditioning and support of high-end substrates (flatness, heat exchange)
2. Heat removal from actuators (thin walls, roughness)
3. Integration of several motion degrees of freedom in small assemblies (fatigue and roughness).

Manufacturing specifications

Based on the functional specifications for high tech applications, six key manufacturing specifications were indicated.

1. Surface flatness (SF): interface (for exchange) between a part and a vulnerable counterpart;
2. Roughness (Ra): low roughness for vulnerable contact; vacuum application and facilitation of cleaning; some roughness for cooling channels to increase heat transfer;
3. Geometric (profile) tolerance: interface accuracy
4. Minimal wall thickness: magnetic permeability and thermal conductivity, saving space in electro-mechanical actuators
5. Small features/channels: holes in air bearings, internal channels
6. Permeation: no leakage when using an internal cooling agent, mainly aimed at vacuum systems.

Manufacturing specifications for conventional machining

Manufacturing experts and mechanical designers were interviewed regarding the present manufacturing performance for high tech parts. Based on their expertise, manufacturing specification for conventional machining (milling and turning) were consolidated in *Table 1*, for ultra-precision machining as well as for standard machining of parts in the range 100-400 mm.

Table 1 Performance of conventional machining and AM in respect to key specifications for parts found in the high tech sector

Specification type		Ultra-precision*	Standard 100-400mm	EBM***	LBM***
Surface flatness	[μm]	5	10-50	n/a	n/a
Roughness (Ra)	[μm]	0.05	0.8-3.2	20-30	5-15
Geometric tolerance (profile)	[μm]	± 2.5	$\pm 20-80$	± 300	± 100
Minimal wall thickness	[μm]	400	400-600	600	200
Small features /channels**	[μm]	190	1000	200	400
Permeation (leakage)	[mbar/l*s]	1×10^{-9}	1×10^{-9}	600	600
Contamination (0.5 $\mu\text{m}/5 \mu\text{m}$)	particles/ m^2	3520/20	3520/29	Unknown	Unknown

* State of the Art

** Smaller features can be obtained through EDM or laser cutting

*** Highly dependent on part design, material, machine type and manufacturing process parameters

Manufacturing specifications for AM

The current manufacturing performance of metal powder bed fusion was obtained from literature for Electron-Beam Melting (EBM) and Laser Beam Melting (LBM) [1]. Table 1 summarizes average values, for standard available metals (powder). It is clear that AM without post-processing is not applicable for our customer's high-end applications.

An example of a typical high-end application is a thermal conditioning table for silicon wafers (Figure 1). The table has a very flat top surface with an air bearing that supports the wafer and facilitates heat exchange in order to control the wafer temperature. It is currently manufactured in aluminum, with a single point diamond turned top surface.

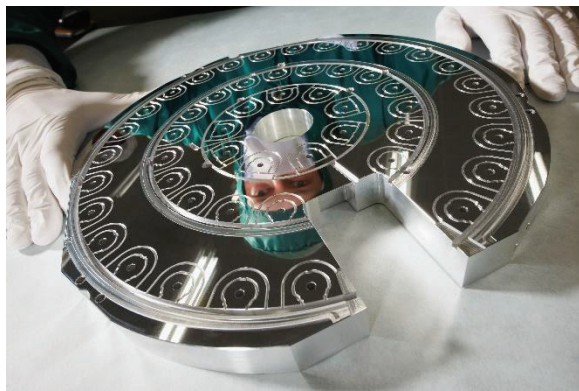


Figure 1 Thermal conditioning plate

TEST CASES

Three cases were identified, based on the above mentioned functional specifications. The cases were used as carriers to investigate whether functional specifications and subsequent

manufacturing requirements can be met using AM to manufacture parts (with optional post-processing). All cases consisted of the design and production of an AM part, including post-processing. All cases were successfully produced with LBM (Figure 2, Figure 4, Figure 6).

Case 1 – Flatness samples

As part of the thermal conditioning table design as presented in [2], test samples were manufactured to investigate surface flatness (after milling) for printed honeycomb structures in stainless steel and aluminum.

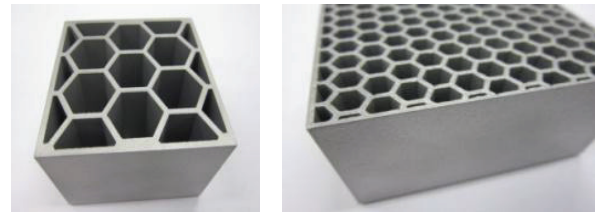


Figure 2. 75x75mm aluminum surface flatness verification samples (2 mesh sizes)

These honeycomb structures could provide the required stiffness and stability to an ultra-flat thermal table like in Figure 1.

The top surface of each aluminum sample was milled in three steps using a cutter of $\phi 100$ with 7 teeth at a turning speed of 1500 turns/min and a feed of 300 mm/min, removing 0.03 per step. After the removal of 0.5 mm the sample flatness was measured using a Zeiss Calypso multi-sensor.

The stainless steel samples were milled with similar strategy and were measured after each

removal of 0.5 mm of thickness. The surface flatness was measured using 25 points on that milled surface. For both materials the range of achieved surface flatness was 9-11 μm , which is similar to what normally can be achieved with such milling operations.

The surface of the aluminum samples showed some cavities than may indicate porosity of the printed metal.

Case 2 – Thin walled cooling structure.

The driver for the second case was the housing of an actuator with internal cooling circuits. The thin-walled housing facilitates heat extraction (thermal conductance, in kW/K) using water, with minimal influence on the magnetic field of the actuator. This resulted in the following mechanical requirements: no permeation, zero porosity and very thin walls ($\leq 0.3 \text{ mm}$).

Two types of structures with internal cooling channels were designed and manufactured. The first cooling structure was a classic meandering cooling channel. The second sample had an internal pillar structure, see Figure 3.

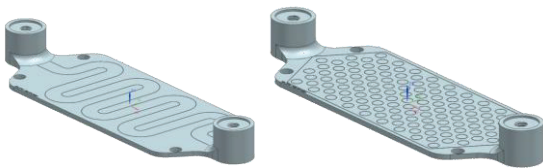


Figure 3. Design for the thin walled (0.3 mm) cooling structures, with a common cooling channel (left) and an open pillar structure (right).

Both designs comprise a very small wall thickness of 0.3 mm and a cavity height of 0.6 mm. The available aluminum LBM process did not facilitate these small features and titanium has a low thermal conductivity. Therefore, it was chosen to build both designs from stainless steel. The two designs were built using LBM and were oriented in the vertical building direction (Figure 4).

On arrival both samples were checked for their accuracy and functionality. Here it was found that:

1. The surface was rougher (R_a in the order of 5-10 μm) than milled faces and metal sheet.
2. The integrated designed thread, in this case M3, was not usable, i.e. we were

not able to connect a M3 thread coupling.

3. Mounting holes were not round, therefore unusable (screws didn't fit) and needed rework.

Both samples were tested for leakage by applying air pressure at one end and closing of the other end while immersed in water. The test showed both sample types were not free of leakage. Hence, the thin walls did not meet the requirement of porosity combined with a small thickness.

However, when performing a Helium leakage test on an isolated part without macroscopic-leakage, a sufficiently low permeation of less than $1 \cdot 10^{-7} \text{ mbar}\cdot\text{l/s}$ was found, which indicates that the internal structure of the material is dense enough to create structures without permeation.



Figure 4: Stainless steel printed thin walled cooling structures.

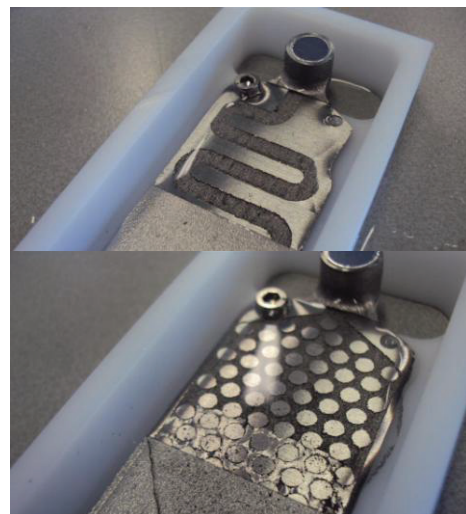


Figure 5: Water was applied on both AM parts showing AM particles from the cooling circuit, with the common part (upper) and pillar structure (below). AM Particles came from the closed circuit.



Figure 6: Ti-6Al-4V printed flexures

Partially removing the walls of the cooling system showed a high roughness on the inside of both parts in respect to the outside of the parts.

When water was applied on the remaining interfaces still a large amount of AM powder came out of the cooling circuits (Figure 5).

Case 3 – Flexures

A compliant test part was designed with two integrated leaf springs. For leaf springs, fatigue strength is the most important parameter, which is closely related to the roughness.

Printed flexures impose a problem regarding surface roughness. A leaf spring with a rough surface has an enlarged change of failure when fatigue loading is applied. [3]

Flexures are normally made in tool steel, which is not applicable in AM. Therefore the flexures were made in Ti-6Al-4V, resulting in similar strain performance for this application. Five flexures were printed in Ti-6Al-4V (Figure 6).

A fatigue testing set-up has been designed to experimentally verify failure behavior for flexures (Figure 7). A voice coil actuator drives the flexure. A constant deviation is realized at a

frequency of about 30 Hz, allowing for accelerated testing for fatigue.

Several flexures are tested, with different finishes that yield different values for surface roughness, which are expected to yield different fatigue behavior:

- No additional finish, powder blasting only
- Two different supplier proprietary finishes that produce a smooth a surface
- EDM post processing, yielding surface roughness typical for current flexures.

The roughness that is realized by an LBM process is higher than typically used for flexure parts. However, the roughness is characterized by less steep cuts so the impact on fatigue failures for flexures is not directly clear.

Fatigue testing and surface post-processing tests are currently in progress.

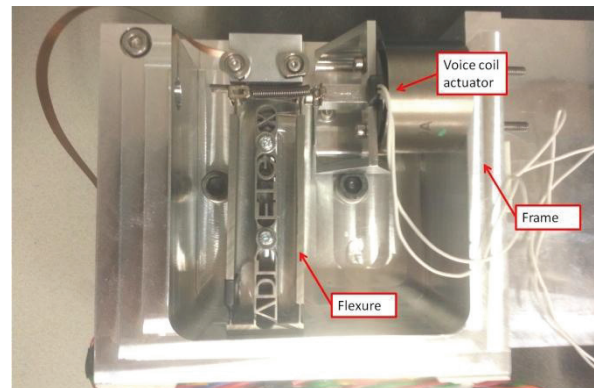


Figure 7: Test set-up to test flexure life-time and stiffness.

Table 2: Initial results for case 1-3 and verification part (V)

Specification type	Case #	Outcome after post-processing & testing
Surface flatness	1	10 μ m
Roughness (Ra)	2; 3	5-10 μ m on the outside Inner surface visually had a higher observed roughness
Geometric tolerance (profile)	2	M3 thread was not possible
Minimal wall thickness	2	> 0.3 mm
Small features / channels	2; 3	< 0,6 mm
Permeation (leakage)	2; 3	<1·10 ⁻⁷ mbar.l/s

CONCLUSION

The paper shows that specialized post-processing is an essential part of using AM machined parts for high-end equipment applications. The typical requirements for these parts cannot currently be met directly by AM processes.

From initial experimental verifications, summarized in *Table 2*, it can be concluded that AM is a promising technology. However, parts realized with AM still require additional attention, which starts during the design phase.

To meet the standards required for this industry, we need to look at:

1. The finishing operations to provide precise interface surfaces
2. Cleaning of internal structures
3. Leakage of thin walls
4. Roughness related to fatigue – can AM manufactured parts be readily used?

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MAXIMISING DIMENSIONAL ACCURACY FROM ADDITIVE LASER MELTING BUILDS

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INTRODUCTION

Additive laser melting (ALM) is a technology that is emerging from the world of rapid prototyping into mainstream manufacturing. It offers many advantages for part production when compared to conventional manufacturing technology groups such as casting, forming and material removal. Whilst these new potentials are being widely lauded it's all too easy to lose sight of the fact that ALM is a tool and as such its true potential can only be unlocked by its correct application. Its maximum performance is realised when it is used for the right job in the right way.

It is increasingly common for patient-specific tooth-supported dental restoration frameworks (figure 1) to be manufactured by ALM. These components carry demanding requirements for size, form and finish to ensure clinical efficacy.

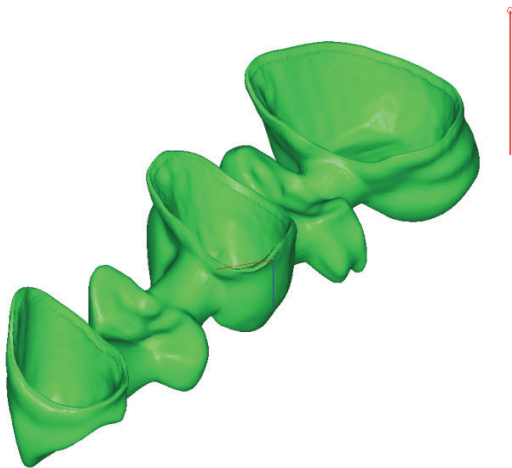


FIGURE 1. Fixed partial denture framework.

I will describe techniques developed by Renishaw to optimise machines in a structured and efficient manner to achieve process capability on the 20 µm tolerances required for tooth-supported restorations. Similar techniques have also been used to meet medical device

process validation requirements and demonstrate process control.

Implant-supported dental restorations (implant abutments and implant bridges, figure 2) are made up of patient-specific freeform surfaces and tight tolerance mechanical interface features.



FIGURE 2. Dental implant bridge, showing implant interfaces uppermost.

I will describe the methods used in Renishaw for efficient design, manufacturing and inspection operations on implant-supported restorations.

DENTAL RESTORATIONS

Description

Dental restorations may be classified in a number of ways helpful to this discussion.

“Direct restorations” are those created during the patient appointment, in the patient’s mouth, and are not relevant to this paper. “Indirect restorations” are created away from the immediate patient appointment, typically by a dental technician. These restorations may be permanently attached, in which case they are termed “fixed partial dentures” (FPDs) or they may be removable by the patient, typically at night.

Restorations may be supported on the patient’s remaining teeth (hence “tooth-supported”, figure 1) or they may rely on dental implants placed in the patient’s jaw during a surgical procedure (ie “implant supported”, figure 2).

Renishaw has been developing ALM-based dental production technology since 2010, focusing on fixed partial dentures, both tooth- and implant-supported. We operate a production facility in the UK supplying frameworks to dental technicians across Europe and can also supply a dental-optimised version of the AM250 ALM machine (figure 3) to customers.



FIGURE 3. Renishaw AM250 additive laser melting machine.

Once in the dental technician's laboratory, frameworks have porcelain or similar materials manually veneered onto them to achieve the required external shape and appearance (figure 4).

Requirements

Dental restorations, whether tooth- or implant-supported must meet requirements including:

1. Strength & fatigue resistance, against chewing and other forces;
2. Biocompatibility, so as to not provoke an adverse physiological response;
3. Morphology, to support porcelain or other veneering materials.

Dimensional accuracy

Dimensional accuracy is a difficult topic for the dental industry. Commonly accepted tests, such as the "Sheffield Test" for implant bridges, are qualitative in nature and rely on operator feel and judgement.

Tooth-supported frameworks must provide a good seal to the prepared tooth. Failure to achieve this may lead to cement wear, periodontal disease or secondary caries. Literature [1-4] suggests that the mean marginal opening should be less than 100 μm . In order to allow for other contributions to the error budget, the ALM process should therefore not exceed a surface profile tolerance (or equivalent) of 20 μm .

The mechanical interface to an implant (which has previously been integrated into the patient's bone) must provide a fatigue-resistant load path for chewing forces, as well as a seal to physiological fluids and associated fluid-borne pathogens.

These requirements results in demanding dimensional and surface finish tolerances, thus these features must be machined. For example, positional tolerances of $\varnothing 25 \mu\text{m}$ and 0.24° for implant bridges and size tolerances of 30 μm or better.



FIGURE 4. Cross-section through porcelain fired onto implant abutment

PROCESS OPTIMISATION

There are a large number of variables affecting the performance and output of ALM systems. In order to optimise an ALM process efficiently and effectively it is essential that these are broken down in a logical manner so that the results of one step in the optimisation process do not invalidate earlier results.

The variables may be classified into three headings: machine, material and part.

Machine calibration

At the machine level (and excluding machine specification parameters such as laser power, spot size, etc), the variables which need to be controlled include:

- Laser output power mapping;
- Beam profile and focus;
- Scan field calibration.

Scan field calibration provides error mapping of the scanning galvanometer angles versus spot position on the powder bed. Renishaw has developed a technique which allows this process to be performed at the customer site. A BoPET (Mylar) sheet with a pre-printed reference pattern is exposed by the laser at low power. Comparative measurements at line intersections are made using a suitable flat bed scanner and custom software on-site. A lookup table correction file, derived from these is loaded back to the machine controller

Material and part parameters

At the material and part level, parameters affecting energy delivery and impacting on surface finish and density need to be considered first. Control of accuracy can then be developed later.

In general Renishaw adopts a design of experiments (DOE) approach to material development. A structured series of experiments are performed to optimise the following features:

- Bulk;
- Side wall;
- Overhanging surfaces;
- Top faces.

These DOE experiments yield material files which may be used to produce a wide range of parts. Customers may be trained to develop parameters to further optimise the process for their own applications or even to develop parameter sets for new materials.

Process validation is performed after optimisation including benchmark builds and mechanical characterisation (tensile, fatigue, hardness, et cetera).

However in the case of the dental applications, the parts are medical devices and therefore require a higher level of verification and

validation. In addition, although they are all unique patient-specific parts, there are certain very characteristic morphological features (figure 1): they are all different but quite similar, and this can be used to our advantage.

The dental optimisation process includes the following stages:

- Process optimisation
 - Surface finish, density
 - Accuracy
- Design verification
 - Mechanical properties
- Process validation

Arrays of parts are built with incremental variation in process parameters. The analysis of these parts gives surface plots such as that shown (figure 5). The least-energy parameters which result in adequate density are selected.

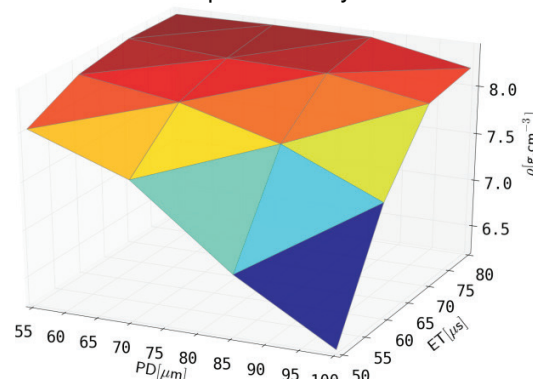


FIGURE 5. Surface plot of part density (ρ) against point distance (PD) and exposure time (ET).

Accuracy measurements are made using an array of geometric parts designed to represent the key features of a fixed partial denture framework (figure 6).

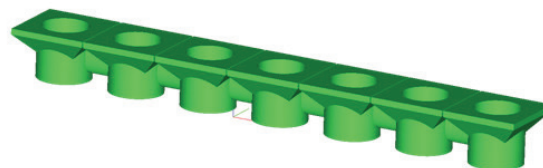


FIGURE 6. Geometric fixed partial denture (pitch 10 mm, overall length 70 mm).

Twelve of these components are laid out to cover the build area. These parts are built, stress relieved then scanned using a desktop scanner (Renishaw DS10, figure 7). The accuracy specification of this scanner is 20 μ m

(ISO 10360-4). However the point cloud data acquired is segmented to extract geometric features and thus dimensions. The resultant averaging leads to at least an order of magnitude reduction in uncertainty.



FIGURE 7. Renishaw DS10 dental scanning machine.

Estimates for the beam spot compensation and XY & Z scale factors are derived from these dimensions. It is also possible to view the variation in these parameters vary around the build envelope (figure 8).

After process optimisation, design verification must be performed to demonstrate that devices produced meet the relevant medical standards. This stage is generic to all production processes and will not be discussed further.

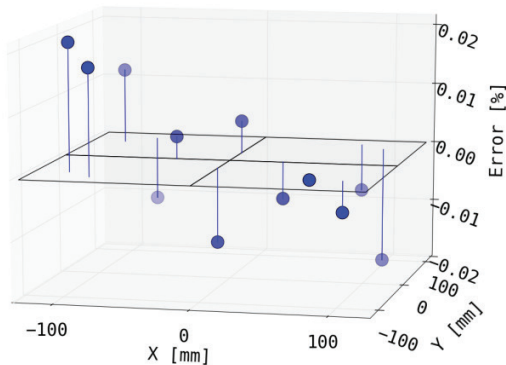


FIGURE 8. XY scale error (percentage points) across build volume.

Process validation using the same geometric parts is performed in order to demonstrate that the production process is capable of consistently producing good parts (figures 9 & 10).

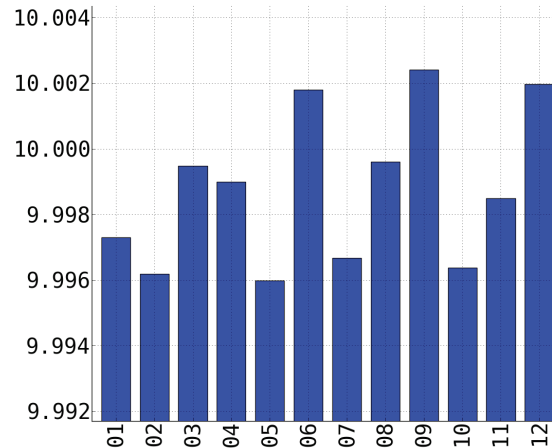


FIGURE 9. Pitch results from all parts on one validation build (all within $\pm 5 \mu\text{m}$ of nominal).

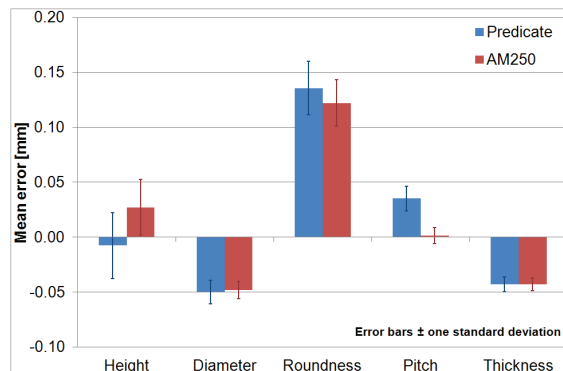


FIGURE 10. Comparison of mean errors (over repeated validation builds) from AM250 and predicate system.

Once in production, machines for dental applications are subject to continuing process monitoring to ensure that the medical devices produced continue to be safe and effective.

ADDITIVE/SUBTRACTIVE OPERATIONS

An additive-only process produces suitable parts for tooth-supported restorations, however this is not adequate for implant-supported devices. A hybrid additive-subtractive model is therefore adopted instead.

In order to provide fixturing of printed parts during secondary operations, implant-supported frameworks are integrated onto kinematic hubs. These hubs provide a repeatable, stiff location for machining and inspection operations and allow support for full-arch bridges or multiple shorter parts (figure 11).

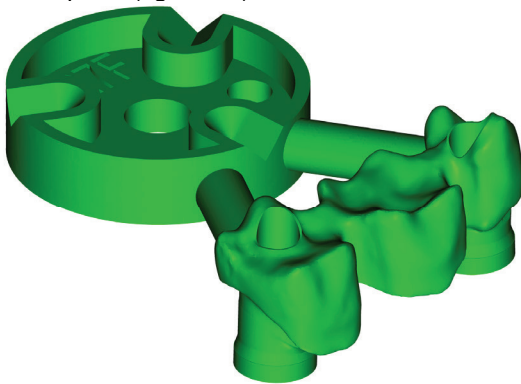


FIGURE 11. Implant bridge attached to hub (only one bridge shown for clarity)

Dental technicians using Renishaw or third-party dental CAD/CAM systems submit orders via the internet. These orders contain STL files defining free-form surfaces and XML files defining the implant interface type, position and orientation information. These orders are received into the Renishaw Dental Manufacturing Suite (DMS) which is a platform designed to manage, track and support all dental production operations with minimal operator intervention.

On receipt, STL files are automatically checked for flaws, being healed and simplified as required. Machining allowances are automatically added to the STL file based on knowledge of the specific implant interface design required at each location. Connectors are automatically placed to join the implant bridge to a numbered hub, although these are presented to an operator for manual adjustment if required.

Parts are printed in CoCr or Ti6Al4V, then stress relieved and routed to machining. NC subroutines have been created for the machining of each implant interface design supported by DMS. CAM software macros automatically generate the NC program using the implant interface type, position and orientation information originally supplied in the XML file.

Once at the 5-axis machine tool, a fixture (figure 12) locates the part in a known position and orientation so that machining can be undertaken with minimal setup time or unnecessary probing.

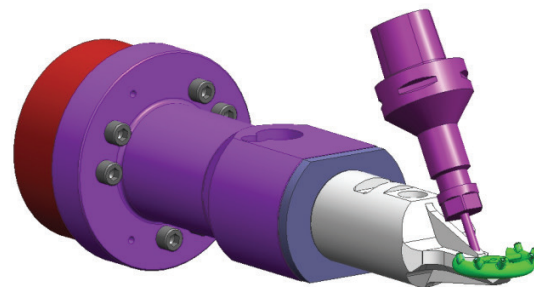


FIGURE 12. Machining fixture with component (green) and cutter shown articulated.

All implant bridges are fully inspected on a DNC CMM. A similar arrangement of automatic program generation is used. Inspection results are logged in DMS and a certificate to accompany the part to the dental technician is produced.

This process has been in production for less than a year but the initial signs are very encouraging in terms of customer feedback, reliability and cost.

CONCLUSION

ALM and hybrid manufacturing which results in dimensional accuracy of parts produced without compromising important metrics such as throughput and yield is possible. The approaches outlined are being used in real world applications by Renishaw and its customers to produce parts with high levels of performance in terms of size, form and finish.

This paper shares the benefits of Renishaw's extensive research and development work centred on the utilisation of ALM for the production of parts with demanding requirements.

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FINISHING OF ELECTRON BEAM MELTED TITANIUM (Ti6Al4V) USING SHAPE ADAPTIVE GRINDING TOOLS

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INTRODUCTION

Electron beam melting (EBM) is a cutting-edge, additive manufacturing (AM) process used to produce three dimensional shapes by melting layers of metal powder with an electron beam in a vacuum. Unique to this process is not only the presence of a vacuum, but a dual scan of each layer. The first scan serves as a pre-heat stage, and the second scan fully melts the powder. This procedure achieves more uniform part temperature during the process as compared to other AM techniques. The result is a fully dense part with a significant reduction in residual stresses. This translates to material properties that are superior to other AM methods and leads to its wide usage such as in orthopedic implants [1-2]. Unfortunately, for many applications, the resulting rough surface produced by additive manufacturing techniques demand a secondary finishing operation to improve the surface quality prior to being put into practice.

Current methods to reduce the surface roughness include traditional machining for solid structures, chemical etching for porous structures, and laser polishing [2-5]. A reduction to 2-3 $\mu\text{m Ra}$ (originally 22-45 $\mu\text{m Ra}$) was reported for laser additive manufactured titanium alloy parts using laser polishing. Other methods achieve similar results in the order of 1 $\mu\text{m Ra}$.

Although some of these finishing methods have a distinct advantage, such as being able to finish porous structures, their resulting surface roughness is limited. To expand on additive manufacturing's many applications, it is desired to further decrease the part's surface roughness while limiting the number of finishing operations.

In this abstract, we introduce a novel process that uses nickel and resin bonded diamond grinding tools to finish titanium (Ti6Al4V)

workpieces manufactured by EBM, as shown in Figure 1.

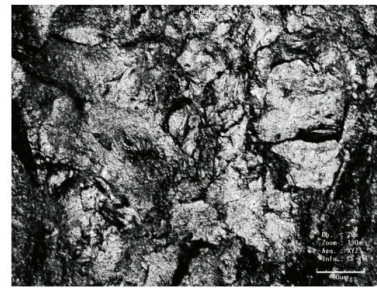


FIGURE 1. Laser microscope image at 20x of a Ti6Al4V workpiece produced by EBM

SHAPE ADAPTIVE GRINDING

Shape adaptive grinding (SAG) expands upon the precessed bonnet concept where an inflated, bulged, spinning membrane-tool is used to polish a surface [6-8]. This tool, termed a bonnet, is previously covered with a polishing cloth and a stream of slurry (e.g. cerium oxide) is directed at the tool and recirculated. As the bonnet presses against the surface of the workpiece (decreasing tool-offset), the contact-spot diameter is increased.

In SAG, however; the inner rubber polishing bonnet (elastic tool) is combined with an outer nickel or resin bonded diamond pad (NBD or RBD). As shown in Figure 2, the deformability of the rubber layer allows the tool to conform to a workpiece's surface during finishing. The workpiece can be of any general shape, including convex, concave, flat, aspheric, or freeform. Simultaneously, however, at smaller scales, the diamond pellets act as a rigid tool and allow for grinding to take place. The result is a flexible grinding process with the benefits of both polishing and grinding techniques. This allows for greater material removal than

standard polishing techniques while producing low surface roughness, and without sacrificing form accuracy.

The spindle speed, attack angle, tool offset, and surface speed of the tool can be actively controlled by a 7-axis CNC machine as it traverses the surface of the workpiece. This allows for control of the grinding spot in order to vary the spot size and removal rate. The air pressure inside the bonnet can also be manipulated in order to further control the force.

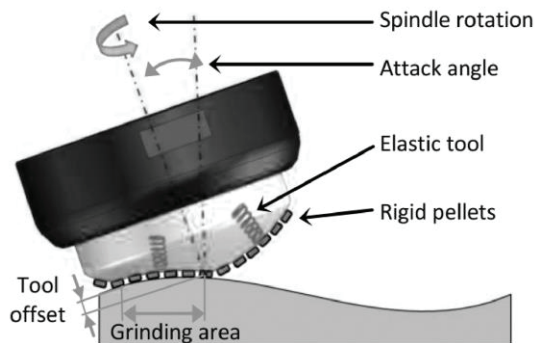


FIGURE 2. Shape adaptive grinding principle

EXPERIMENTAL RESULTS

The Ti6Al4V workpiece produced by EBM shown in Figure 1 was used for the experiments

in this paper. A series of experiments were initially conducted to determine the optimal parameters for this SAG process. A 5 mm x 45 mm flat section of the titanium sample was ground with three SAG tools using the machine parameters given in Table 1 at four separate feedrates (25, 50, 100, and 200 mm/min). With each successive grinding trial, the diamond size of the SAG tool was decreased to achieve an ultra-smooth surface (40 μm NBD, 9 μm NBD, and 3 μm RBD). For each tool and feedrate, a series of grinding runs were performed until no further improvement of the surface was witnessed. Figure 3 shows a laser microscope image at 20x and 100x of the surface after grinding with each tool. Figure 4 shows three-dimensional surface profiles taken with a white light interferometer at 10x magnification.

TABLE 1. Machine parameters

Parameter	Value
Spindle Speed	1500 RPM
Tool Pressure	1.0 Bar
Attack Angle	20°
Tool Offset	0.3 mm
X/Y Spacing	0.2 mm
Feedrate	25, 50, 100, 200 mm/min

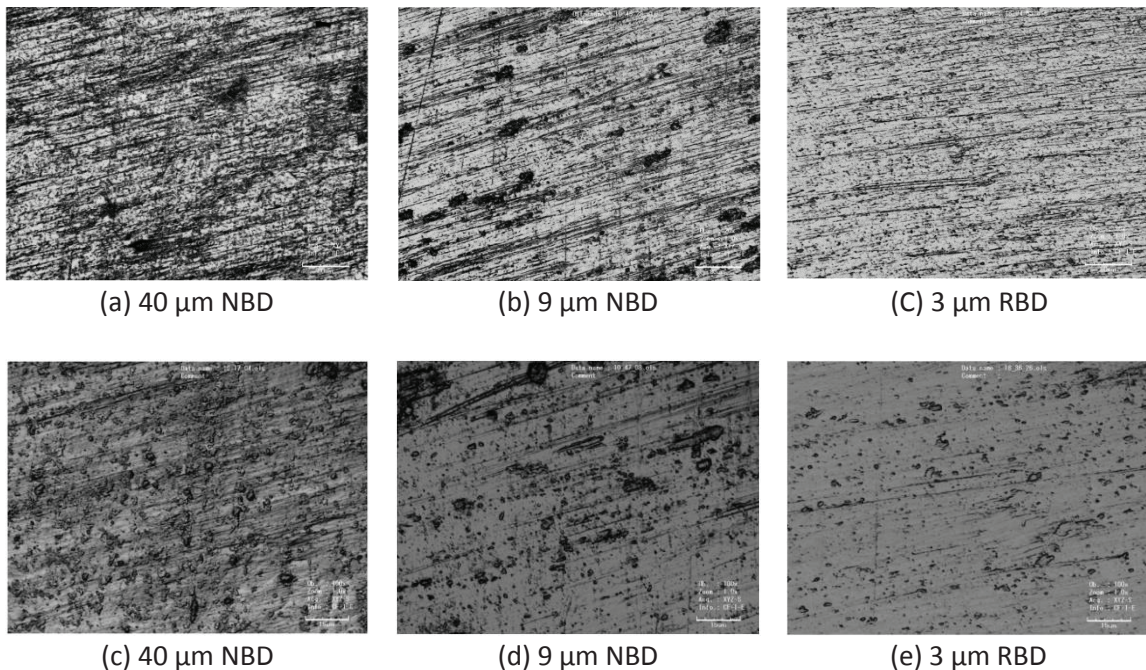
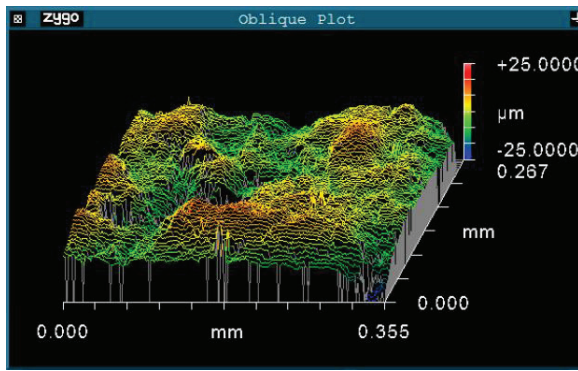
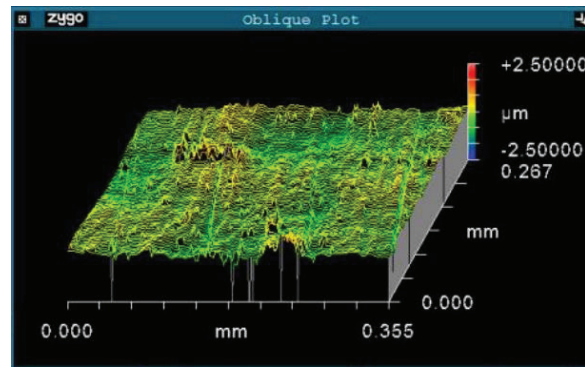


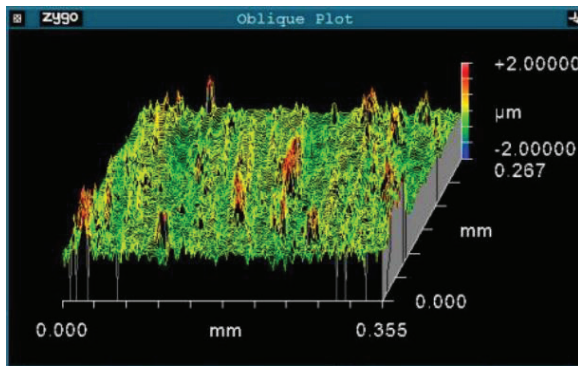
FIGURE 3. Laser microscope images taken at 20X (top) and 100x (bottom) after successive grinding trials



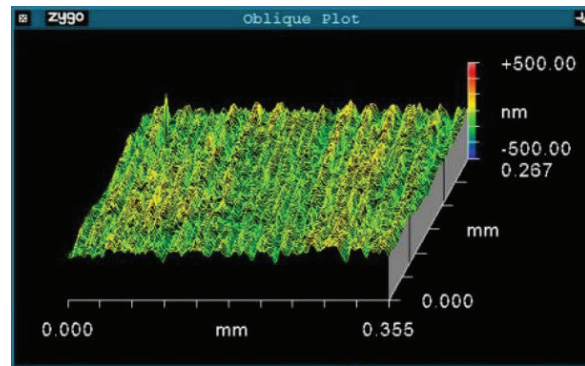
(a) Unfinished surface



(b) 40 μm NBD



(c) 9 μm NBD



(d) 3 μm RBD

FIGURE 4. 3D surface profiles of surface at 10x magnification after successive grinding trials

Due to the rough initial surface seen in Figure 1 and Figure 4(a), a coarse 40 μm grit NBD SAG tool was initially used to remove the layered surface. Figure 3(a and c) and Figure 4(b) show the resulting surface, void of layered material. This allows for further grinding with subsequently finer SAG tools. A 9 μm NBD tool was used next on the same area using the same parameters. Further reduction in surface features is shown in Figure 3(b and d) and Figure 4(c) and a directional surface texture begins to emerge. The final tool used for grinding employed a 3 μm RBD SAG tool. The final surface is uniform with directional scratches as seen in Figure 3(c and e) and Figure 4(d). If desired, further trials using other polishing media could remove the SAG tool marks and further improve the titanium surface appearance.

An optical image of the workpiece is shown in Figure 5. This picture shows the surface condition at each successive grinding process from right to left: after 40 μm grinding, after 40 μm and 9 μm grinding, and after 40, 9, and 3 μm grinding (the left edge of the workpiece shows

the original surface condition). The surface becomes more reflective after each successive grinding trial. In terms of surface roughness variance, it was found that the best results were obtained by using a feedrate of 100 mm/min for the 40 μm and 9 μm NBD SAG tools and 25 mm/min for the 3 μm RBD SAG tool.

The surface roughnesses S_a and RMS at 2.5 x, 10x and 50x magnifications were measured using a white light interferometer (It was not possible to get an image at 2.5x magnification of the initial surface due to its rough nature). The results are plotted in Figure 6 and Figure 7. The surface roughness S_a is drastically improved after the initial SAG process. Additional grinding reduced the final roughness S_a to 50.24 nm, 27.66 nm, and 31.44 nm S_a at 2.5x, 10x and 50x, respectively. The same trend is witnessed for the RMS roughness, with final values of 63.83 nm, 34.56 nm, and 40.37 nm at 2.5x, 10x, and 50x, respectively. This represents a reduction in surface roughness of approximately two orders of magnitude. These results show substantial improvement over current finishing

methods for post-processing of AM parts, opening the door to further applications.

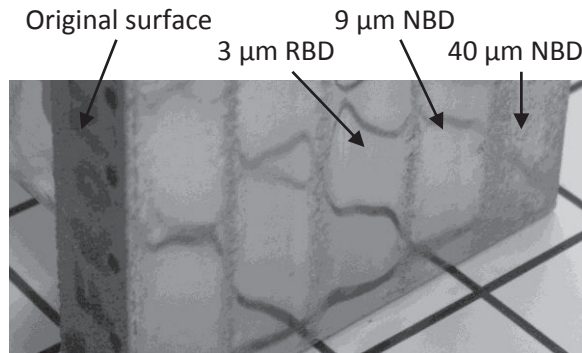


FIGURE 5. Photograph of finished surface

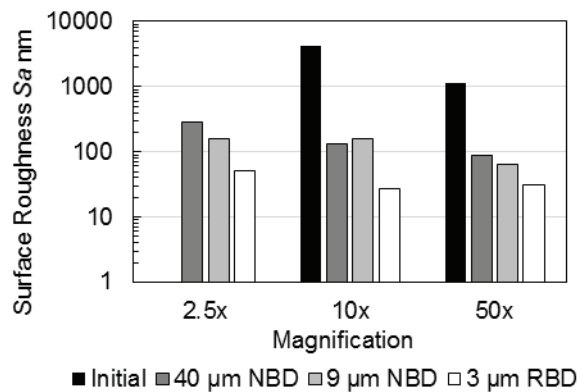


FIGURE 6. Average surface roughness S_a

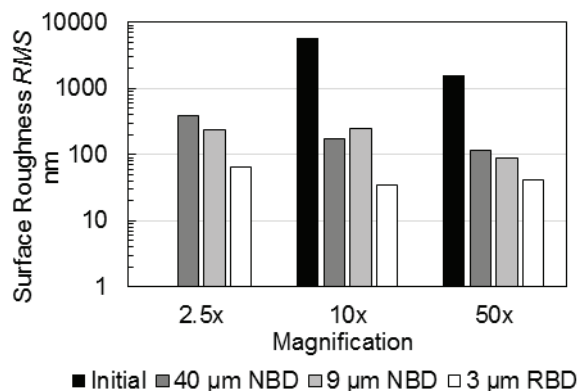


FIGURE 7. Average surface roughness RMS

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Hybrid Manufacturing of Complex Molds and Dies Using Additive Metals and CNC

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Increasingly complex tooling inserts for injection molding and die casting are made possible using a hybrid manufacturing approach. Using the advantages of precision CNC machining with direct LaserCUSING® additive metals technology, inserts can be created with enhanced thermal management properties. CNC and LaserCUSING® processes allow designers to significantly improve the thermal performance of inserts through the incorporation of conformal and parallel cooling channels. Using basic CAD tools, these conformal cooling designs are engineered into the inserts and fused directly on top of insert bases that were created using CNC. This presentation focuses on the synergistic relationship of using CNC and LaserCUSING processes together to produce high performance precision tool inserts for aerospace, medical and automotive applications.

A SOLUTION FOR INDEXING 3D PRINTED PARTS ONTO SECONDARY MACHINING PLATFORMS

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INTRODUCTION

Advances in additive manufacturing processes have enabled the direct production of net-shape parts that meet dimensional specifications in some applications. However for more demanding applications where critical tolerances and surface finish requirements exceed what can be achieved by three dimensional (3D) printing techniques, secondary finishing processes may be employed to machine a near net-shape part to its final form.

One key to utilizing conventional secondary machining methods to finish a near net-shape part is to know the spatial location of all of the features of the part. This is normally achieved by “touching-off” the machining tool onto critical surfaces of a work piece in order to establish a datum in each axis. For the case of a powder bed fusion process such as utilized in a Direct Metal Laser Sintering (DMLS) system, all surfaces of the printed parts may be too rough to accurately determine their spatial location using a touch-off method.

The need for accurately indexing a near net shaped part becomes more critical as a part is printed closer to net shape. If there is an offset in the true position of the printed part that needs only a small amount of excess material removed, one side of a feature may have more machined off while the other side gets machined less.

There are other solutions to this problem such as building directly onto a mounting block in a known location. But this solution is not ideal for the repeated machining of multiple parts. This paper explores a method of defining the spatial location of DMLS printed test parts by incorporating indexing features directly into the printed part. The work also determines the minimum amount of excess material needed to be added to and removed from a work piece to remove all evidence of surface roughness that was created during a DMLS printing process.

PROCEDURE

This work was performed on a maraging tool steel alloy available from the machine manufacturer EOS. The material has a chemical composition corresponding to US classification 18% Ni Maraging 300. Printing was done using an EOSint M280 DMLS machine with standard laser parameters provided by the manufacturer under their Surface Parameter option.

Test blocks with two indexing holes in the bottom surface were printed (Figure 1). Each test block consisted of two near net-shape (slightly oversized) rectangular geometries; a 30 mm square on top of a 40 x 60 mm base. The amount of excess material printed ranged from 0.025 to 0.076 mm on all sides. After printing, and before the test blocks were removed from their build platforms, they were heat treated according a procedure supplied by the manufacture. This was primarily done to relieve internal stresses that build up in the parts during the printing process, but it also results in an increase in the hardness of the material.

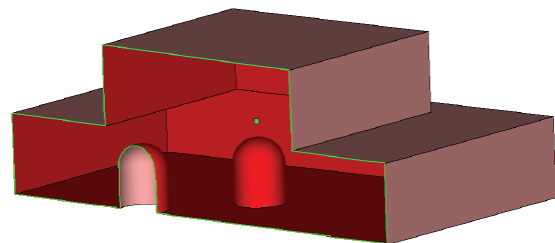


FIGURE 1. Cut-away model of a test block with indexing holes built into the bottom.

The top surface of the test blocks were ground flat in relation to the build platform. Measurements off of the machined surface of the build platform provided the z-axis positioning. After the test blocks were removed from their build platforms, the rough surface inside the indexing holes was machined smooth by reaming while allowing the part to float in the x/y directions. This allowed the reamer bit to

self-center in the indexing holes to maintain the true position of their centers.

The finished indexing holes of the test block were positioned over pins in known locations on a mounting block. A snug fit of the pins into the indexing holes ensured the accurate positioning of the test block relative to the mounting block (Figure 2). Based on the known location of the pins, the clean surfaces of the mounting block were used to locate the position of the test blocks, and the excess material of each block was machined by surface grinding without any direct measurements made to the test blocks themselves.

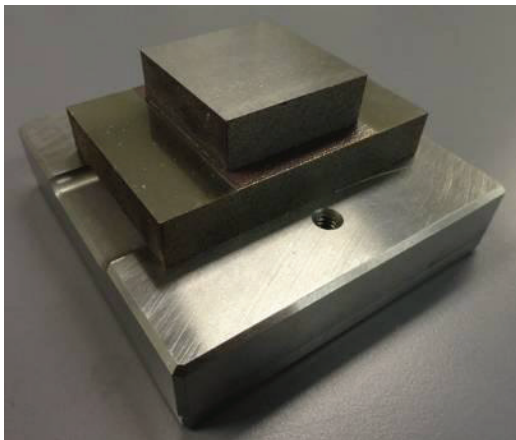


FIGURE 2. Test block with rough side walls positioned onto the mounting block.

RESULTS

After machining off the excess material from each of the test blocks, they were visually examined for the extent of roughness removed, the evenness of the finish around the block, and they were measured for dimensional accuracy. Figure 3 shows views of the rough surfaces of the as-printed test block and the test block that had 0.025 mm excess material added and machined off. It was estimated that approx. 50 % of the roughness was eliminated with the removal of 0.25 mm of material.

Similar views are shown for the test blocks that had 0.051 and 0.076 mm excess material added and removed are shown in Figure 4. Machining 0.051 mm from the surfaces removed on the order of 80 % of the roughness. In removing 0.076 mm of material, there was no evidence of surface roughness on any of the sides. Furthermore, since the machining used a stepwise process, it was determined that all of

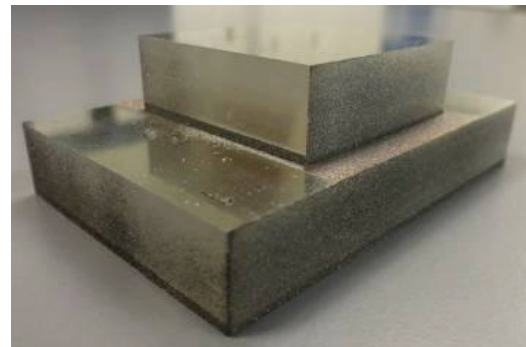
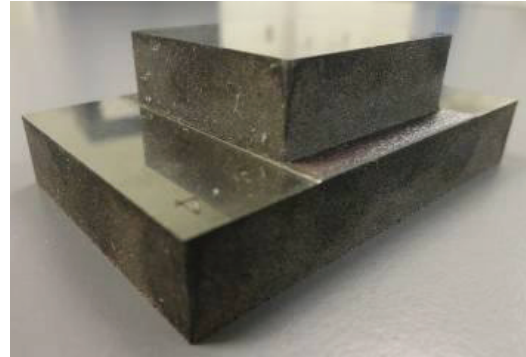


Figure 3. Surface roughness of test blocks as-printed (top) and machined by 0.025 mm (bottom).

the surface roughness was eliminated after 0.06 mm of material was removed.

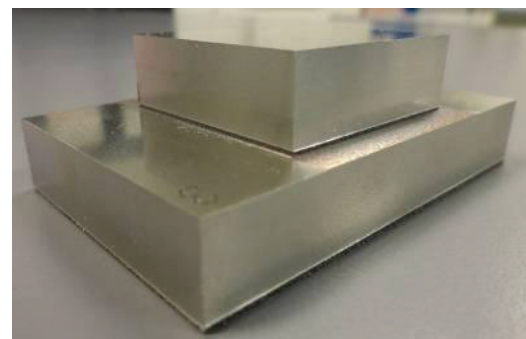
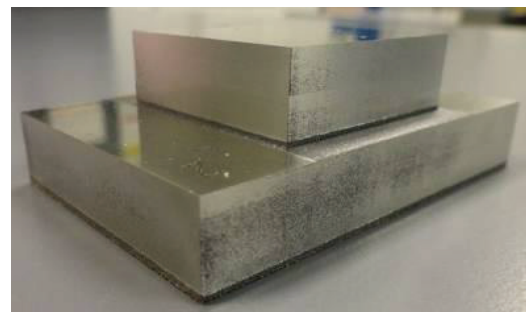


Figure 4. Surface finish of test blocks machined by 0.051 mm (top) and 0.076 mm (bottom).

For each test block, the method of fixturing to and indexing from a fixed mounting block resulted in accurate dimensions in both the 30 x 30 mm square and the 40 x 60 mm rectangular base of the test blocks to within 0.01 mm. Based on the evenness of the surface finish of the test blocks during and after machining, it was estimated that the average error in positioning the test blocks onto the mounting block was within 0.01 mm as well.

CONCLUSION

It was demonstrated that slightly oversized, parts can be accurately machined in relation to indexing holes incorporated into DMLS-printed parts. Based on the positional accuracy of this indexing method, a printed part need only be oversized by 0.076 mm (0.003 in.) in order to remove all of the surface roughness caused by the DMLS printing process through a minimal amount of secondary machining. This indexing solution may be extended to more automated secondary machining processes such as multi-axis milling and sink electrostatic discharge machining to reduce the time associated with both set-up and machining.

History and Development of Process Control for Additive Manufacturing

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ABSTRACT

Starting in the late 1980's, several new technologies were created that have the potential to revolutionize manufacturing. These technologies are, for the most part, additive processes that build up parts layer by layer. In addition, the processes that are being touted for hard-core manufacturing are primarily laser or e-beam based processes. This presentation will give a brief history of Additive Manufacturing and give an assessment of the process control for these technologies. These technologies initially grew out of a commercial need for rapid prototyping. This market has a different requirement for process and quality control than traditional manufacturing. The relatively poor process control of the existing commercial Additive Manufacturing equipment is a vestige of this history.

This presentation will discuss this history and discuss improvements in quality over time. The emphasis will be on Additive Manufacturing processes that are being considered for direct manufacturing, which is a different market than the 3D Printing "Makerbot" market. Topics to be discussed include past and present machine sensors, materials, and operational methods that were used in the past and those that are used today to create manufactured parts. Finally, a discussion of new methods and future directions of AM process control will be presented.

CT to Evaluate of Distortions in Stainless-Steel AM Structures

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ABSTRACT

High-spatial resolution computed tomographic (HRCT) imaging has been used to evaluate two as-built stainless-steel truss test artifacts fabricated by LLNL. The artifacts were fabricated via laser powder bed fusion using a Concept Laser M2 machine [1]. Additive manufacturing (AM) shows significant promise towards revolutionizing manufacturing. With additive manufacturing, parts which could not be manufactured before are feasible, making available a new level of functionality and capabilities to designers. HRCT offers insight into tolerances achieved by AM and deviations from the design.

TEST ARTIFACTS

One method to evaluate the performance of an AM machine/process is through the production and evaluation of test artifacts. The test artifacts studied were built in 316L stainless steel. The first test artifact [Fig. 1(Top)] is a combined cubic and octahedral (will be referred to as a cubic) truss with 3-mm unit cells. The 1.5-mm squares within these planes are supported with vertical struts at every intersection. Diagonal struts intersect the square structure at alternating intersections. The terms horizontal and vertical are arbitrary, but they do correspond to the orientation of the structure during both the fabrication and imaging processes.

The octet artifact [Fig. 1(Bottom)] is a 3x3x3 lattice composed of 4.5-mm octet truss unit cells. The octet truss has been a focus of significant interest in the field of microarchetected materials [2-5]. It combines high structural stiffness with low density in order to achieve material property ratios (e.g. modulus/density) outside the range found in natural materials [2,4,5].

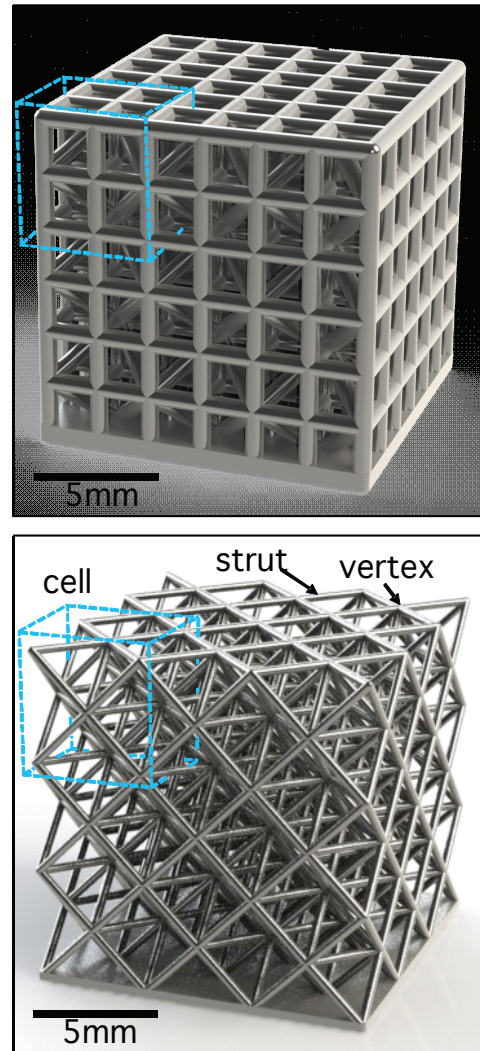


FIGURE 1. Top: 3D rendering of the cubic test artifact identifying the repeating cell element. This is a 3x3x3 cutout of the full 5x5x5 measured artifact, scaled for comparison to the octet artifact. Bottom: 3D rendering of the octet test artifact identifying the repeating cell element.

[†] This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

This test artifact is composed of repeating cells of struts, where each strut is aligned at 45° angle to two of the main axes and 90° to the third. The cell geometry is the sum of an octahedral cell combined with a tetrahedral cell [4,5].

Four identical copies of the octet artifact were fabricated at a laser power of 60 W and speed of 0.6 m/s. The lattice truss artifacts were sent in pairs to CT metrology systems at Zeiss [6] and LLNL. The measurements of dimensional variability provided a gauge of both the quality of the build (lattice failure rates, structural deviations) and consistency between builds via the comparison of multiple identical copies.

MEASUREMENTS

Evaluation of the test artifacts can be performed using either or both geometrical structure based surface methods such as Coordinate Measurement Machines (CMM) and/or material information using voxel based methods like HRCT. HRCT offers both a surface and a voxel based analysis of the artifacts while surface methods cannot provide the voxel information. To enable evaluation of the internal structure quality, we used HRCT to obtain information about the geometrical (surface) and physical material properties (voxel based) of both test artifacts. The cubic artifact was used for technique development.[7] The octet artifact is of more interest and is the focus of the quantitative analysis.

The test artifacts were imaged at 200 kV and 0.2 mA on an LLNL HRCT system called CCAT using 250 μm of Cu filtering. For the cubic artifact, 360 projections over 360 degrees were acquired. For the octet artifact, 1440 projections were acquired over 360 degrees. The data was reconstructed using a 3-D Feldkamp algorithm implemented in the LLNL ImageRec software [8]. The projections were reconstructed into 18- μm isotropic voxels with a spatial resolution of $\sim 55 \mu\text{m}$. The voxels are in linear attenuation coefficient (LAC) units which are a function of the CT system energy response, and density and elemental composition of the material. Assuming that the composition does not change, the difference in LAC values is a function of density.

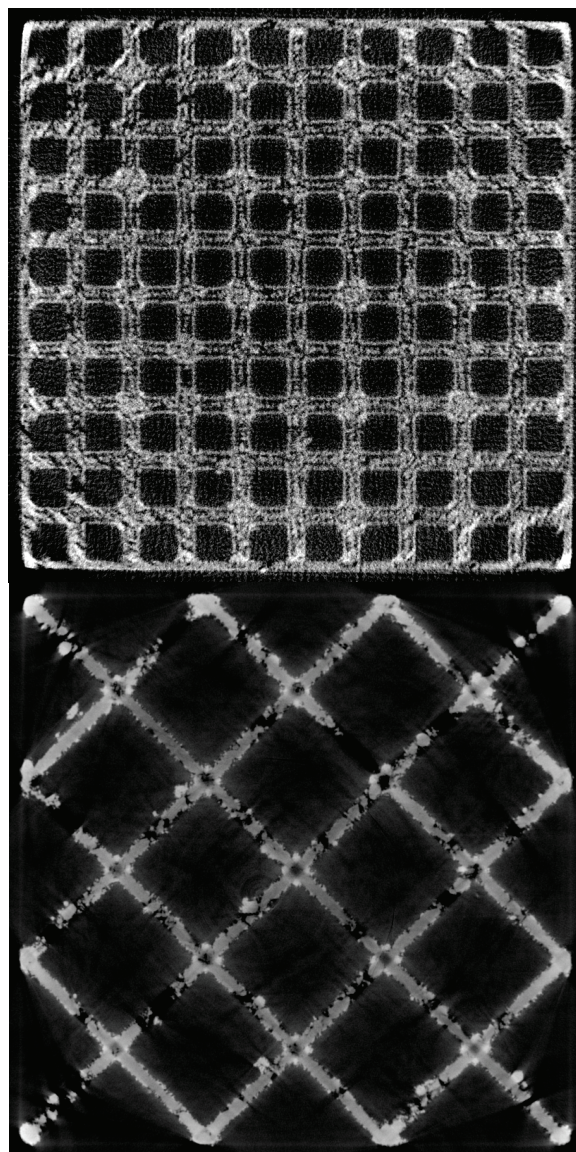


FIGURE 2. A 2D horizontal cross-section extracted from the HRCT volume of the cubic (top) and octet (bottom) test artifact near the center of the CT volume. Bright and dark voxels represent material and air, respectively.

To better understand the structure, it is helpful to review and analyze 2-D cross-sectional images. Horizontal cross-sections through the cubic and octet test articles are shown in Figure 2. The predominant dark voxels amongst the struts are air, lack of material. For the cubic artifact [Fig. 2(top)], the rectilinear ribs, are $\sim 0.55\text{-mm}$ outer diameter. The image reveals that the struts are not full density. The diagonal struts intersection positions with the vertical columns can be seen as a thickening at alternate intersections. For the octet artifact [Fig. 2(bottom)], the cross sections

also reveal that the struts are not full density and that the interior vertices generally have a large central void, which is connected to broken horizontal struts.

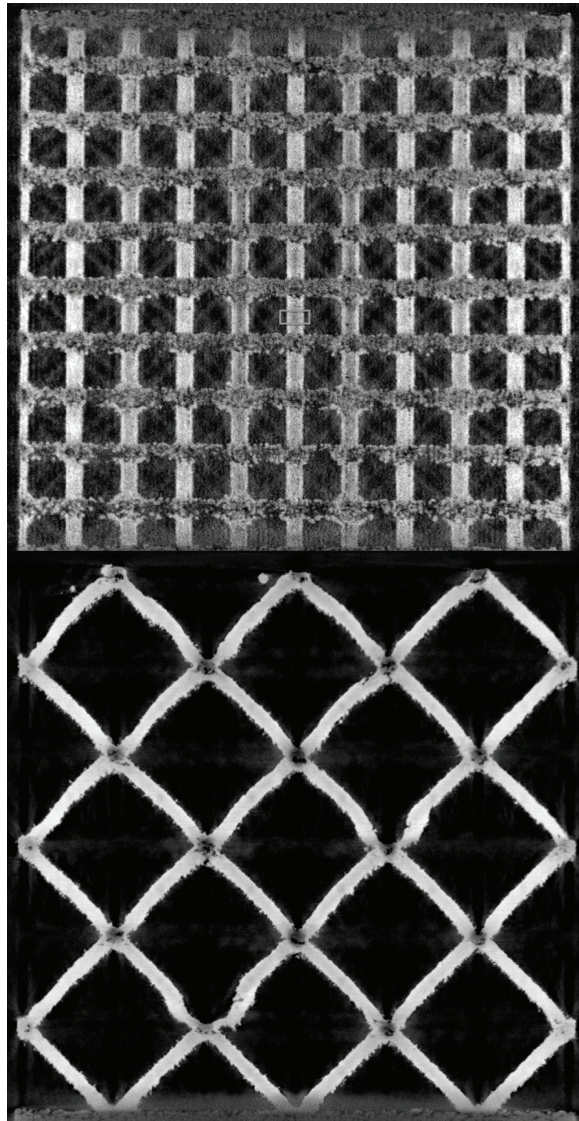


FIGURE 3. A vertical cross-section through the center of the cubic (top) and octet (bottom) artifacts. Bright and dark voxels represent material and air, respectively.

Vertical cross-sections are shown in Figure 3. Fig. 3(top) shows that the vertical columns in the cubic artifact have a higher and more uniform density than the horizontal struts. The octet artifact is shown in Fig. 3(bottom). The diagonal struts are solid with minimal density fluctuations.

ANALYSIS AND DISCUSSION

The critical first step in analysis of HRCT data is to determine the dimensions, vertices, principal axes, etc. and to compare HRCT data to a CAD model in determining the optimal threshold for surface extraction. Ideally, the LAC distributions are well separated and the optimal threshold is easily determined. A histogram of the voxel values helps in determining the threshold(s). Histograms for the octet artifact are shown in Figure 4. The segmentation regions of interest, e.g., horizontal and vertical struts, were determined by the CAD model and result in different regions within the histogram.

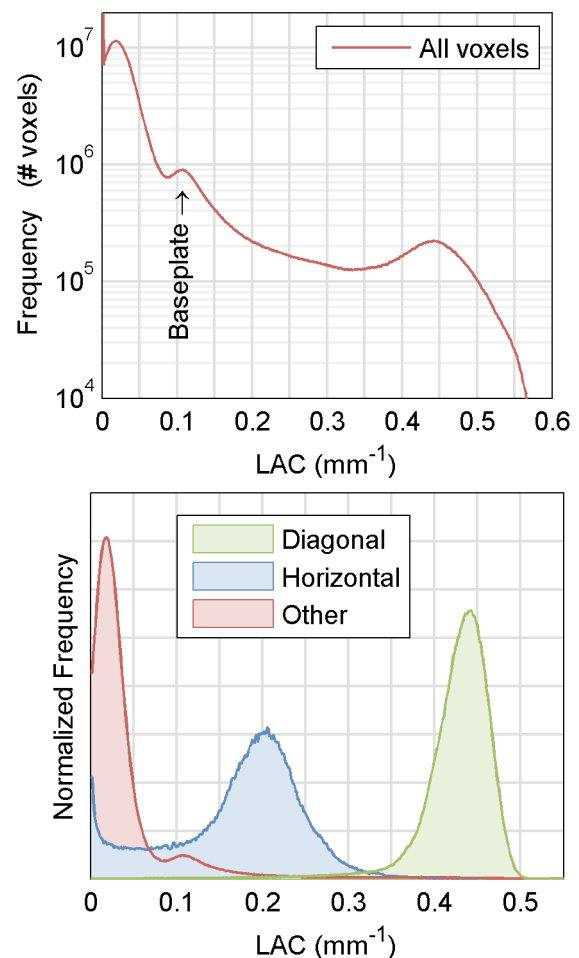


FIGURE 4. Top: LAC histogram for all voxels in the octet artifact. Bottom: The normalized histograms for the horizontal struts, diagonal struts and the volume remainder. Note that the LAC (density) of the horizontal struts (0.2 mm^{-1}) are ~ 2 times less than the diagonal struts LAC (0.47 mm^{-1}).

The statistical variation in these parameters was characterized using the following semi-automated methodologies:

- 1) The CAD model was registered to the CT volume using an intensity least-squares algorithm.
- 2) 70 x 70 x 180 voxel sub-volumes are extracted around each strut based on the CAD model locations.
- 3) Each sub-volume was thresholded at 0.14 mm^{-1} which is 30% of the median diagonal LAC value, 0.47 mm^{-1} [see Fig. 4(Bottom)]. For each cross section the centroid is determined along the center 2/3rds of the strut.
- 4) The sequence of the centroids was the centerline.
- 5) The strut principal axis was determined by a linear fit to the centerline.
- 6) The intersection of the struts' principal axes was used to determine the as built vertices.

Examples of the extracted strut subvolumes are shown in Figure 5. The connectivity analysis uses the 3D volume, but for visualization, the subvolumes are compressed using maximum intensity projections (MIP) where each pixel is the maximum voxel value along the projection direction. MIP images are helpful for visualizing the overall structure, but may hide breaks not aligned with the projection direction.

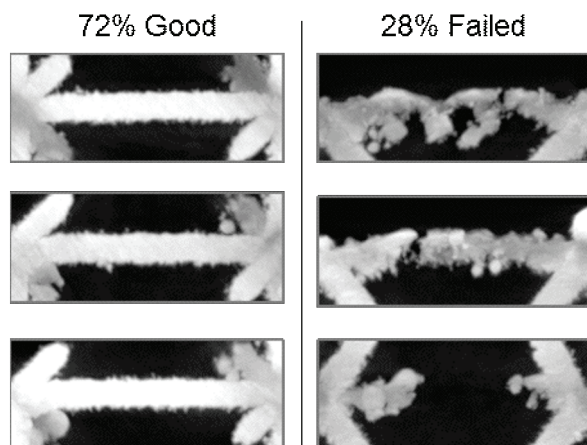


FIGURE 5. Side-view maximum intensity projections of good and bad struts in the octet artifact. Struts “fail” if their LAC value or diameter value falls below 0.14 mm^{-1} or $100 \mu\text{m}$, respectively.

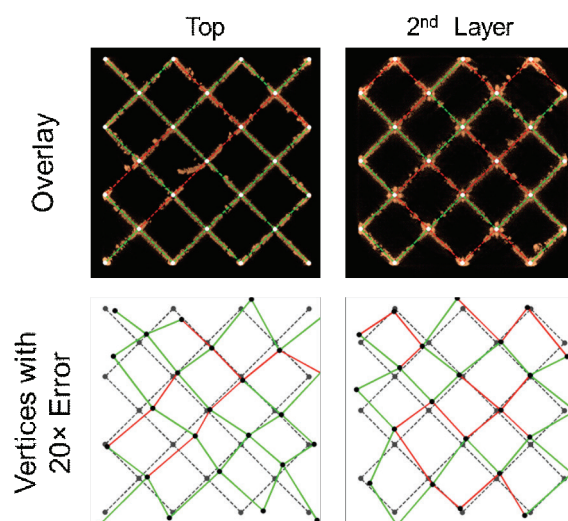


FIGURE 6. Top: Horizontal slices through the top two layers. The struts' principal axes are overlaid in green and red dashed lines for connected and broken struts, respectively. Bottom: The as-built vertex error is computed relative to the CAD model and is magnified 20x in the lower row.

In the octet artifact, 720 struts were analyzed for connectivity. 14% were broken with gaps exceeding $50 \mu\text{m}$, another 14% have single voxel gaps, or are connected with a thin bridge of material (diameter $< 100 \mu\text{m}$). The remaining 72% of struts have an average diameter of $370 \mu\text{m}$, and which on average narrows down to $\sim 340 \mu\text{m}$.

The estimated vertex position for the top two horizontal layers is shown in Figure 6. The vertex position is estimated by finding the least squares intersection point of the adjacent good struts. The average vertex error increases with height, increasing from $25 \mu\text{m}$ in the first layer above the baseplate to $90 \mu\text{m}$ in the topmost layer. The layers excluding the topmost layer are within $\sim 50 \mu\text{m}$ of the CAD model with two exceptions. First, a majority of the interior vertices are hollow. Second, approximately 5% of the interior diagonal struts show significant drooping near the lower vertex.

The HRCT measurements are able to identify several issues with the parts and fabrication that will be used to improve the second round fabrication. The measurements in Figures 2-4 show that the horizontally fabricated struts have higher variability in position, geometry and density than the vertically aligned struts. The failed struts, as shown in Fig. 5, appear to

predominantly occur in the horizontal plane. These issues may be improved by angling the truss during fabrication to avoid generating any struts on the purely horizontal plane. Fig. 3 shows that the vertices often contain voids, and the lower part of the vertical struts is often slightly bent. This may be due to a thermal or a support issue during fabrication, and may be improved by altering the design geometry or fab parameters around the vertices. Finally, Fig. 6 shows that the position error of the vertices does not follow any large scale repeatable trend that can be easily removed by adjusting the input geometry. The variability is increased with height, however since this is a stochastic error it is not removable via calibrating the input file.

SUMMARY

Computed tomography is unique in its ability to obtain both surface geometrical and interior material information to evaluate complex additive manufacturing technology parts. LLNL developed HRCT hardware and software analysis methods are designed to analyze the structure and material properties of materials and complex objects that make this a practical tool in the development of additive-material technologies. This knowledge can be used to both adjust the design and the fabrication process to improve the lattice truss strength and reliability. New octet trusses are being built given the feedback from the HRCT results to optimize the parameters to yield better trusses.

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Dimensional accuracy of internal channels in SLM produced parts.

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INTRODUCTION

Due to its layer-by-layer additive manufacturing technique, the Selective Laser Melting (SLM) process enables the production of metallic parts with complex features and internal cavities. Today this leads to various applications in medical, automotive and aeronautical industries. These high-end applications however also require extensive quality control. By Computed Tomography (CT), internal features can be measured in a non-destructive manner, which makes this measuring technique utterly suitable for SLM-produced parts. This work will indicate the structural error between the dimensions of the design and the final product for internal circular features in SLM.

EXPERIMENTAL

All parts in this work were produced by Selective Laser Melting. The KU Leuven's in-house built SLM machine is equipped with a 300 W fiber laser with a spot size of 80 μm . Test bars with dimensions of 80x20x10 mm were produced in AlSi10Mg. These parts were scanned with a laser power of 300 W and a scan speed of 1600 mm/s, resulting in 99.5 % relative density [1]. The test bars contain internal channels with diameters ranging from 0.4 to 4 mm. Test bars were produced in both XY-orientation and Z-orientation (Figure 1).

For dimensional metrology of the inner cavities, a Nikon Metrology XT H450 CT scanner was employed. With a voltage ranging up to 450 kV, this CT scanner is well equipped for penetrating thicker structures and materials with a high attenuation coefficient compared to standard CT scanners for dimensional metrology [2].

As a second measuring technique, a Mitutoyo QuickVision optical coordinate measuring machine was used. This technique is only employed for imaging and verification, since this requires a destructive approach.

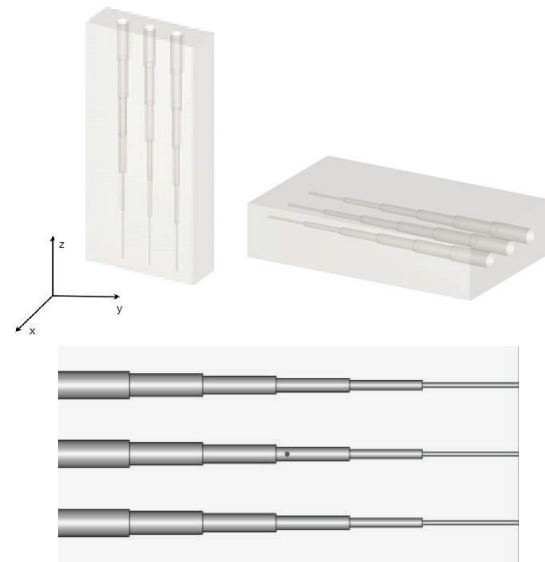


FIGURE 1: Design of test bars, produced in both Z- direction (top left) and XY-direction (top right) and a cross section (bottom)

RESULTS & DISCUSSION

By CT metrology, the diameters and roundness of all channels were determined. Later, the test bars were cut perpendicular to the channels. These internal channels were verified by Quick Vision optical measurement. Here the diameters of the maximum inscribed and minimum circumscribed circle were measured to get an indication of the deviation of the channels from their designed circular shape and dimensions.

The roundness of the channels was determined by calculating the difference between the radius of the minimum circumscribed circle and the radius of the maximum inscribed circle, both circles being concentric. The roundness is indicated in mm. The relative roundness was defined as the ratio between the roundness factor [mm] and the channel diameter [mm].

Z orientation (Vertical channels)

Figure 2 indicates the dimensional error on channels that were produced vertically, measured both by CT and optical. A first observation shows that the results by both measuring techniques correlate very well. The error is independent of the designed diameter. Every channel is about $150\text{ }\mu\text{m}$ smaller in diameter. This is due to the lack of dimensional offsets. As the CAD design indicates the laser path to be followed, it does not take the width of the melt pool into account. The contours of the CAD data indicate the path of the center of the laser spot. While the formed melt pool has a width of $120\text{ }\mu\text{m}$ to $150\text{ }\mu\text{m}$ (for AlSi10Mg in these processing conditions), the actual contour of the part will be shifted by $60\text{ }\mu\text{m}$ to $75\text{ }\mu\text{m}$. For inner circular shaped features, this results in a diameter decrease of $120\text{ }\mu\text{m}$ to $150\text{ }\mu\text{m}$. For this material and these processing parameters, we can conclude that a compensation offset of $150\text{ }\mu\text{m}$ is needed on the total diameter.

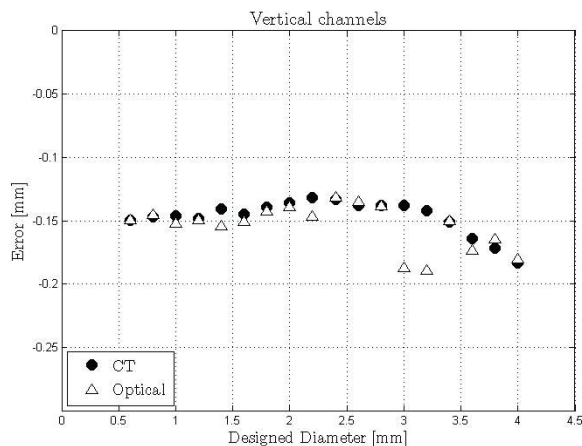


FIGURE 2: Dimensional error on vertically produced channels.

XY orientation (Horizontal channels)

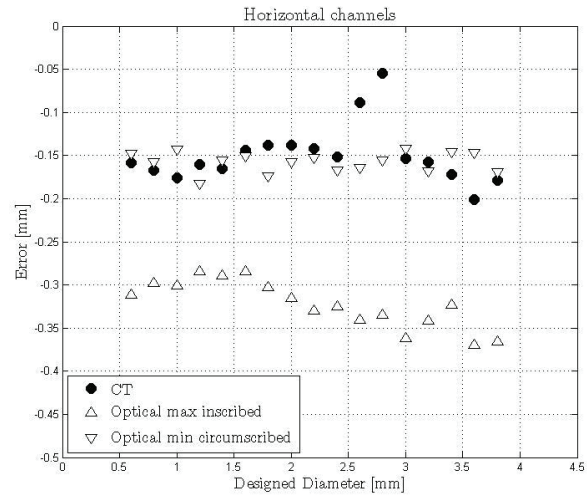


FIGURE 3: Dimensional error on horizontally produced channels.

Unlike the good correlation between optical measurement and CT measurement in the vertical channels, this seems not to be the case for the horizontal channels, as concluded from Figure 3.

This discrepancy is elucidated by observing the cross sections for each channel in each building direction in Figure 4 (Note that this is only one cross section of a 16 mm-long channel, thus not showing an overall representation of the entire channel).

The horizontally produced channels strongly deviate from their designed circular shape, which is not the case for the vertically produced channels. It is clear that for horizontal channels, another phenomenon has an important influence on the channel's dimensional accuracy.

This observation is quantified by roundness measurements performed by both CT dimensional metrology and optical measurements (Figure 5). While the vertical channels reach a relative roundness below 0.05, the horizontal channels only have a relative roundness between 0.05 and 0.26.

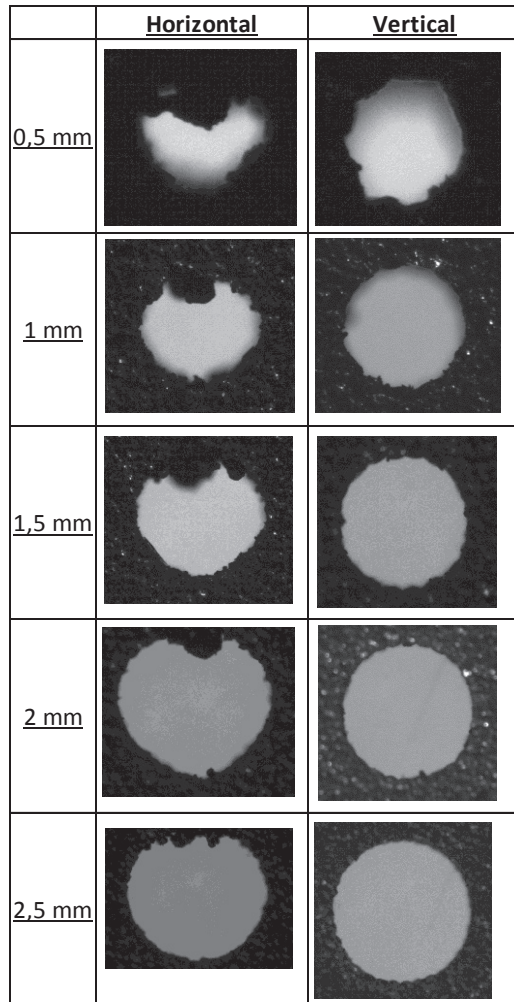


FIGURE 4: Optical cross section of all channels produced in two directions.

A second quantification of this form deviation in horizontal channels was done by optical measurement. The diameters of the maximum inscribed and the minimum circumscribed circle were measured. From Figure 3 we can see that the maximum inscribed circle somewhat resembles the diameter measured by CT, while the minimum circumscribed circle is about 150 μm bigger in diameter. Because this difference in inner and outer diameter is consistent for all designed channel diameters, we can conclude that the phenomenon causing this roundness error is independent of the channel's dimensions. However, as we can see from the optical images in Figure 4, the proportional error becomes smaller for bigger channels. This is also shown in Figure 5, where for horizontally produced channels, the relative roundness decreases for increasing diameters. For vertical

channels, the relative roundness is approximately constant, with exception of the very small channels, where the irregularity of the melt pool becomes more influential to the roundness.

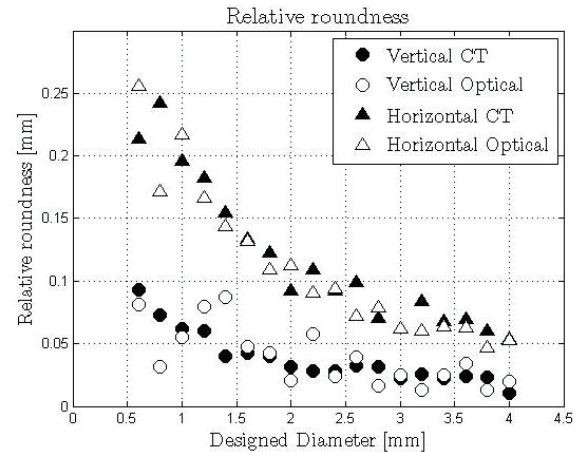


FIGURE 5: Relative roundness of vertical and horizontal channels.

Cause of this form deviation on horizontal channels is undoubtedly the building direction of the channel. Because in horizontal channels, the top layers of the cavity are scanned on loose powder, there is a different kind of heat dissipation than when a layer is scanned on a previously solidified layer. When scanning on loose powder material, the melt pool sinks deep into the powder material and leads to cross formation. This cross formation in so-called 'down-facing structures' is a phenomenon that is very hard to control due to the random nature of the powder particles' packing, leading to a varying heat conductivity.

Compared to the offset compensation that was used to compensate the dimensional error in vertical channels, this problem however is harder to solve. Possible solutions are: i) re-orientation of the part, ii) shape compensation, iii) parameter adaptation or iv) re-design of the part.

i) Re-orientation of the part

This does not include any functional changes to the part's design, only a rotation of the part with respect to the baseplate. By re-orientation of the part, the manufacturer can avoid horizontal channels. A good example is the test part in Figure 1. Building the part in XY-direction is hard, because then, all channels are built

horizontally. By rotating the part 90° over the x-axis, all channels can be built vertically, and thus with higher dimensional accuracy.

ii) Shape compensation

Because the depth of the dross formation can be measured, and in a further state perhaps even predicted based on process parameters, material, environment, etc. , one could compensate for the dross formation in the shape design. For instance: design of an ellipse, that with the formation of dross, would result in a circular shape.

iii) Parameter adaptation

Another way of tackling this problem is by trying to minimize or avoid the dross formation by parameter optimization. Dross can be minimized by forming a melt pool that is less deep. This can be done by lowering the laser power, or by increasing the scan speed, so that the energy input is lowered.

iv) Re-design of the part

If all other options fail, the designer could re-design the part in such a manner that it still fits the customer's requirements, but horizontal channels are avoided.

CONCLUSIONS

Vertically produced channels have to be compensated by the width of the melt pool, since the contours of the CAD data indicate the movement of the center of the laser beam, and not the border of the melt pool. This compensation factor depends on the melt pool width, and thus on the process parameters and the powder material.

For horizontally produced channels, the same compensation factor for the width of the melt pool has to be applied. On top of that, a form error is induced by dross formation. The amount of dross formation is dependent on the base material and the applied process parameters, but dross formation is irregular in shape and thus hard to compensate.

Four ways to deal with dross formation are: re-orientation of the part, shape compensation, parameter adaptation and re-design of the final part.

ACKNOWLEDGEMENTS

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QUALIFYING MANUFACTURING VARIABILITY USING ANALYTICAL COMPUTED TOMOGRAPHY OF DIRECT METAL LASER SINTERED TEST STRUCTURES

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ABSTRACT

Additive manufacturing (AM) of metal parts using direct metal laser sintering (DMLS) or selective laser melting (SLM) processes remains an enticing prospect for a variety of industries, but as with many other AM processes, concerns about the reliability, reproducibility, and dimensional accuracy of the process linger [1, 2]. It is widely suspected that the choice of part orientation, support structures (placement, shape, and number), and fine tuning of machine parameters applied during a build are critical to the quality of the final result. Because of these opportunities for user-defined build variations, the decisions of the tool user(s) are not trivial, and may even be implicated in some build failures. While an experienced user or OEM using tuned tool parameters may produce ideal builds, little is known about the range of variability encountered among different shops using such processes independently. This is particularly true for 'one-off' parts which may not have the time or funding to permit extensive testing to achieve the best final product possible. Because of this variability, there appears to be a degree of art required for successful use of the DMLS process, and the implied learning curve should be accounted for when considering adoption. This study seeks to illustrate the variability encountered among lead users, by asking several of them to perform the same build and comparing their results.

A test block (Figure 1) was designed to evaluate the fidelity of a typical product produced by job shops using EOS DMLS systems, who were then asked to build the test part from the same supplied CAD model with no dimensional requirements given (no pass/fail), to simulate the

typical interaction with an AM job shop, where a final part is returned to the user.

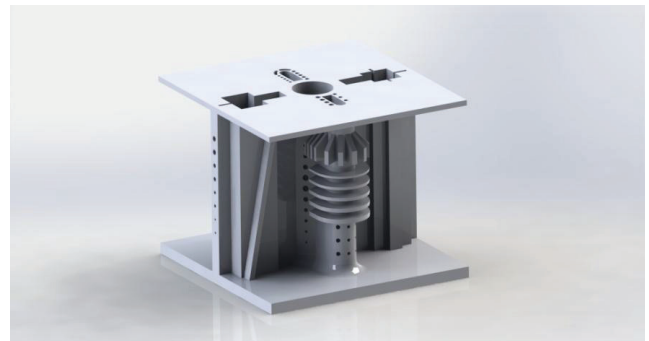


FIGURE 1. The test block CAD Model (ideal).

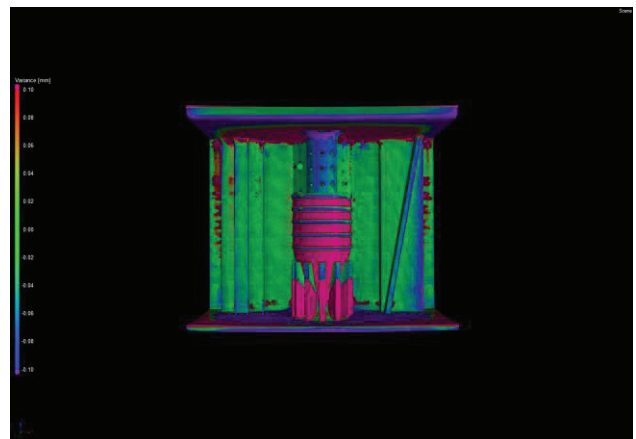


FIGURE 2. Surface comparison of a DMLS test block, with residual support structure remaining. Deviations beyond $>+0.1\text{mm}$ from the expected surface are in pink, deviations $>-0.1\text{mm}$ are in purple.



FIGURE 3. Cross section of internal piping structures of test block. Blue lines denote STL boundaries. Residual supports can be seen.

Three job shops with AM capabilities were selected from a list obtained from EOS based on the number of DMLS systems in shop, in an effort to select from an experienced set of users. All parts were made from GP1 (EOS 17-4 SS) using orientations and supports chosen by the tool users. Significant defects were observed visually in each printed part, including rough surfaces and distorted or misshapen regions, though the character and location of these defects varies from sample to sample. To further quantify variability these parts were scanned using a GE vltomelx computed tomography (CT) system, for analysis of part fidelity [3]. This work attempts to quantify the dimensional variability observed while giving possible explanations for both the particular defects of each test block and the defects which are shared among the set, as well as recommendations regarding design methods for optimizing build supports to maximize final part fidelity.

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Assessment of Guidelines for Conducting Round Robin Studies in Additive Manufacturing

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INTRODUCTION

There is strong demand in the additive manufacturing (AM) community for guidance in conducting round robin studies. This topic was one of the consensus-based priority action items identified in the Measurement Science Roadmap for Metals-Based Additive Manufacturing for accelerating widespread use of AM [1]. Further, ASTM International Committee F42 on Additive Manufacturing and the International Organization for Standardization (ISO) Technical Committee 261 on Additive Manufacturing identified in their Joint Plan for AM Standards Development the need for high-level round robin standards broadly impacting AM [2].

The desire for round robin studies likely stems from the need for qualification and certification of parts used in critical applications. Qualification and certification of aerospace metallic materials is well defined and very rigorous, often requiring thousands of tests, millions of dollars, and five to fifteen years to complete [3]. Many in the AM community see round robin testing as a way to distribute the burden of qualification by having multiple institutions contribute to the process. However, accomplishing this requires some guidance on conducting the round robin studies as well as an examination of round robin tests themselves.

EXISTING STANDARDS

Round robin, or interlaboratory, studies involve multiple institutions each performing a defined task following an established procedure, and returning the result of that task. This type of examination is very common in evaluating measurement methods. In fact, both ASTM and ISO have standards detailing how to conduct interlaboratory studies to evaluate measurement methods [4,5], as well as documents summarizing these standards [6, 7]. All of these documents emphasize that the purpose of the round robin study is to evaluate the “precision”

of the measurement method by calculating repeatability and reproducibility statistics.

The fact that a round robin study is primarily an investigation of reproducibility is important because many in the AM community may want round robins to provide more. A round robin study is not intended to investigate the sensitivity of an output with process variables; this is better accomplished in a factorial design of experiments or a ruggedness test [8]. A round robin study is not necessarily a method to collect part performance data for qualification and design allowables. The study must be completed and acceptable reproducibility demonstrated before anyone knows if the gathered data is appropriate for these purposes. Also, a round robin study is not intended as a benchmarking study to determine which machine or system performs best.

While most of the space in ASTM E691 and ISO 5725-2 is devoted to the statistics involved in evaluating the various measurement results, there is important guidance in each about how to conduct the round robin study. For example, both standards discuss the study membership (study coordinator, statistician, participants), the design of experiment, the preparation of materials, etc. The control in these experiments (i.e., what is sent to all the laboratories in the study) is always the material. The focus of the experiments (i.e., what is being evaluated) is the measurement method. The outcome of the each test (i.e., what is returned to the study coordinator) is the measurement result.

ANALOGY TO AM

It is possible to draw an analogy between round robin studies for evaluating measurement methods and round robin studies for AM. In an AM round robin, the control would be the design of the part to be built. The outcome would be the fabricated part. The focus of the experiment,

however, is not necessarily as clear. An initial inclination might be to say it is the AM process that is being investigated. However, there are many more variables involved in producing an AM part than only the AM process (e.g., properties of the raw input material), and it is certainly conceivable to conduct a round robin study where participating laboratories build parts with multiple AM processes. It is likely more accurate to say the focus of an AM round robin is to evaluate the manufacturing plan.

THE MANUFACTURING PLAN

The manufacturing plan is a set of instructions on how to build a part. ASTM standard specifications for AM materials require the need for a manufacturing plan and suggest that the plan include the machine(s) to be used, the properties of the raw material, pre-determined process parameters (i.e., machine settings), traceable digital files, process steps, post-processing procedures, and more [9]. However, there is still no definitive or minimum set of variables that should be specified in the manufacturing plan.

ASTM E691 states that a valid, well-written measurement method (the analog to a manufacturing plan) should exist prior to initiating the round robin study and that the measurement method should have been subjected to a ruggedness test. A ruggedness test is essentially a full factorial design of experiments investigating effects of various factors on the outcome [8]. The idea is that the ruggedness test would reveal what level of control should be placed on the individual variables. However, the number of factors or variables in a single AM process is extremely large and the types of processes are diverse. While there is certainly literature on the sensitivity of density, residual stress, mechanical properties, etc. to several process parameters, a complete test is impractical.

In the absence of a complete ruggedness test, manufacturing plans in AM round robin studies that NIST has participated in have either been extremely prescriptive or extremely unregulated. The more prescriptive manufacturing plans have had sections prescribing the part geometry and build orientation, machine requirements, raw material (including chemistry, particle size and distribution, recycling of powder, and powder handling), process setup and machine parameters (including recommended

calibrations, building platform requirements, beam settings and beam path strategies, and build chamber environment), in-process requirements and recording, process completion requirements, post-processing, and reporting. These studies not only specified the raw material required to build the parts, but also supplied the virgin powder to each participant. The more unregulated study asked participants to procure their own powder (stating only that the material should be appropriate for the participant's chosen system) and asked participants to develop their own machine parameter set. However, both manufacturing plans are perfectly acceptable and appropriate for round robin study. The more unregulated plans encompass many machines and machine types that have differing requirements and capabilities. The more prescriptive plans govern only one machine type. Unfortunately the results of these studies are not yet available.

Since the manufacturing plan will apply to all participants in the round robin study, the procedures and instructions must be applicable and accessible to each and every participant. Many users make tweaks and improvements to their systems and procedures that help make higher quality products more consistently. If other members of the participants list have not made those same tweaks and improvements, the results of the round robin will likely be skewed. Some users might see these tweaks and improvements as a competitive advantage and may not be willing to share them with the entire group. Others in the group may not be able to make the tweaks and improvements because of various system limitations. The consequence is that the common procedure followed by all participants will be dictated by the capabilities of the least flexible or experienced participant.

DIFFERENCES IN AM STUDIES

While there is a good analogy between round robins for measurement methods and for AM, there are some key differences due to the uniqueness of AM that warrant examination. One obvious difference is in the outcomes of the round robins. The statistics that characterize the measurement method are calculated directly from the measurement results returned from each laboratory. In AM, each participating laboratory returns the physical parts; further measurement must be performed before any statistics can be calculated (i.e., there is an

additional step). A difficulty with this is that there are a large number of measurements that can be performed on the returned parts, from dimensional measurement to mechanical testing to metallography, and more. As such, the results of one round robin with a scope limited to a small number of measurements cannot fully describe the “precision” of a manufacturing plan.

Post-processing presents an interesting challenge to characterizing additive manufacturing systems. Very few AM parts, especially metal parts, are used directly out of the machine. Most parts require post-processing, whether that be machining to achieve a certain geometric tolerance or surface roughness, or heat treatment to relieve residual stress and attain a desired mechanical strength. However, if the post-processing is part of the manufacturing plan and is conducted at (or by) each laboratory, then the round robin study encompasses more than just additive manufacturing. On the other hand, if parts are tested directly out of the machine, their performance data may not be truly indicative of parts used in actual applications. This latter case is problematic for qualification. A likely compromise is to have participants return parts right out of the machine and allow the study coordinator to arrange post processing of all parts by a reputable vendor.

The control in AM round robins (the design file) is also not as simple as one might originally think. Nearly all AM systems work with the stereolithography (.STL) file format, but these STL files are often generated from computer aided design (CAD) solid models. One should keep in mind that there may be some loss in fidelity when converting from the native CAD file to the STL file. This loss may be of high importance in a round robin examining the part geometry. Further, some AM systems require support structures. Whether the controlled design contains support structures or the process of placing support structures is specified, it is a necessary consideration when designing the round robin study. One should also keep in mind that removing the support structures may affect the final properties (especially geometry) of the part and will likely require specification within the manufacturing plan.

CONCLUSIONS

The uniqueness of AM makes it necessary to develop specific guidance on conducting round robin studies. The existing standards on round robin studies for measurement methods provide excellent starting points for guidance on conducting AM round robins. While differences will surely exist between AM round robins and round robins for measurement methods, the resulting information is likely to be similar. Specifically, the primary result of a round robin study is a measurement of repeatability and reproducibility. This is important for the AM community to keep in mind because by itself, guidance on conducting a round robin is not necessarily the same as ensuring good repeatability and reproducibility. Data showing excellent repeatability and reproducibility will be vital for process qualification. However, repeatability and reproducibility that are acceptable for qualification are likely the products of a rigorous manufacturing plan. Similarly to ASTM E691 recommending that the test method be completed by one laboratory before round robin testing [4], the development of a manufacturing plan should be completed before conducting the round robin and is likely better done within one institution. Without knowing which factors or variables most affect the performance properties of the final part, the results of the round robin studies are extremely specific. Tightening or loosening control of one variable, or changing the value of the variable, may significantly alter the results and therefore require a new round robin and complete re-qualification. Yet, a well-conducted round robin study, especially one focusing on part geometry, can go a long way toward demonstrating that AM parts can be built to meet a required tolerance.

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STUDY OF ACCURACY OF PARTS PRODUCED USING ADDITIVE MANUFACTURING

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INTRODUCTION

Additive manufacturing (AM) shows significant promise towards revolutionizing discrete parts manufacturing. Traditional subtractive manufacturing offers a variety of capabilities which can be carried out at a high level of precision, however the range of shapes that can be produced is limited by the access of cutting / abrasive tools to designed features. With additive manufacturing, forms which could not be achieved before are feasible, making available a new level of functionality and capabilities to designers.

The purpose of this presentation is to focus discussion onto the issue of accuracy and uncertainty of parts made with additive manufacturing processes.

TEST ARTIFACTS

One method to characterize the performance of a machine or process is through the production and measurement of a test artifact. A standard test artifact has clear benefits: the same standard artifact produced by different machines or processes can be easily compared. Additionally, if designed properly, the standard test artifact can be used to test machine or process limitations. The standard test artifact can also serve as a method for performance verification between users and vendors, as well

as provide vendors with a platform that allows them to demonstrate improvements in their AM systems.

In the proposed Additive Manufacturing Test Artifacts, we seek a design that can help us identify / analyze the capabilities and limitations of a machine or process, quantify a machine or process accuracy, and provides us with a diagnostic tool for isolating specific machine defects. Further, we seek a design whose features all serve a specific purpose, are simple in design, and are easy to measure with low measurement uncertainty. The primary characterization of the AM system obtained by building and measuring the AM test artifact is via geometric accuracy and surface roughness of the test artifact (see Figure 1). However, because a standardized artifact will be widely employed by many users with a variety of needs, the test artifact and its features must be versatile enough to allow many different types of measurements by a variety of measurement systems.

The test artifact shown in Fig. 1 was built in stainless steel (see Fig. 2) on an EOS M270 powder bed fusion AM system using default machine parameter settings for that material. The part was connected to the build platform with hatched support structures.

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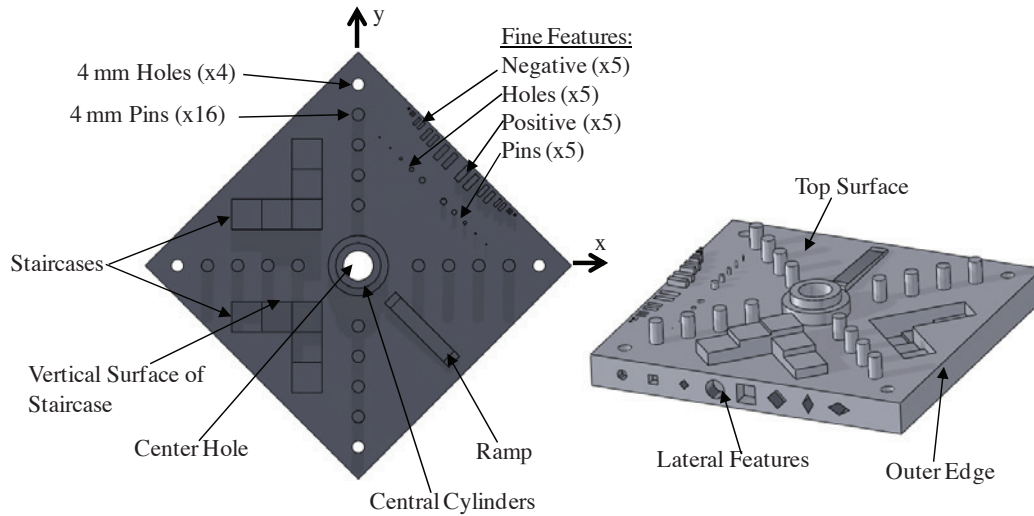


FIGURE 1. Solid model of the proposed test artifact showing a top view (left) and an oblique view (right) with arrows pointing to important features.

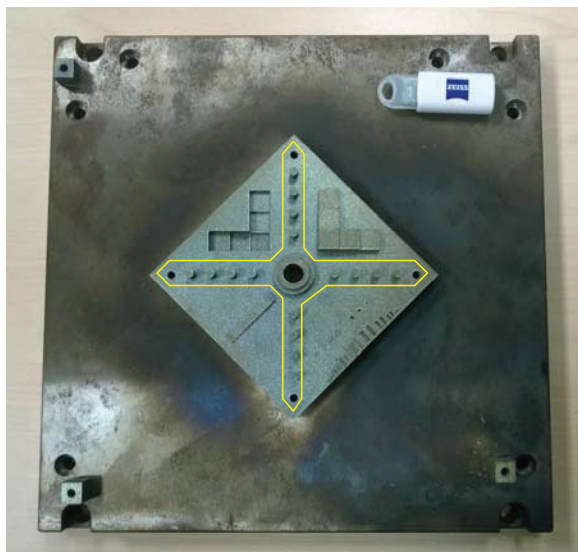


FIGURE 2. Test artifact manufactured in stainless steel. Flatness data was collected along yellow path, with 0.3 mm spacing generating 1,700 points of data

A second test artifact was created to exemplify the type of metrology challenges encountered in present AM parts. This part is shown in Fig. 3 and is a 3x3x3 lattice composed of 4.5mm octet truss unit cells. The octet lattice truss is a microstructural architecture, which combines low density with high structural stiffness. Considered as a macroscopic element, the octet structure can produce material properties outside the range of modulus-to-density ratios found in natural materials.

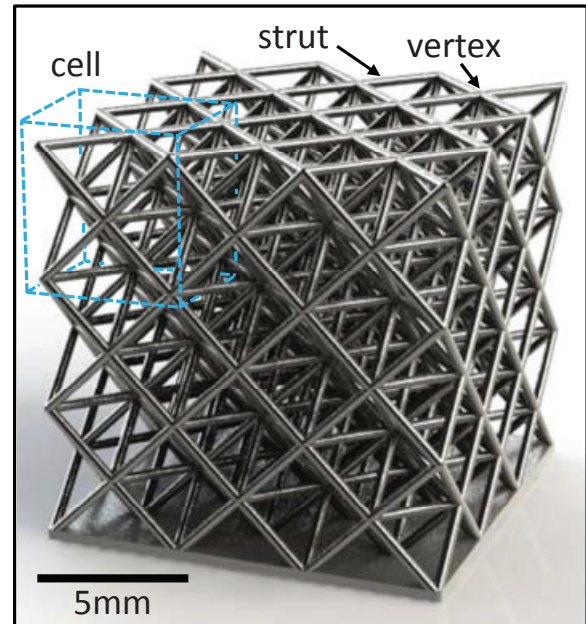


FIGURE 3. Octet lattice test artifact, with edge dimension of 14mm on a side

The lattice truss artifact was fabricated out of stainless steel powder on a Concept Laser M2 Cusing laser additive manufacturing machine. Sets of 4 identical copies of the artifact were fabricated at a laser power of 60W and speed of 0.6m/s over the power bed. The lattice truss artifacts were sent in pairs to computed tomography (CT) metrology systems at Zeiss and LLNL [1]. The measurements of dimensional variability provided a gauge of both the quality of the build (lattice failure rates,

warping) and consistency between builds via the comparison of multiple identical copies. The artifacts were then swapped and the measurements repeated to compare the capabilities of the two CT metrology systems.

MEASUREMENTS

Complexity of the parts will require multiple evaluations with optical, tactile and X-ray sensors. The main focus will be on defining the geometric accuracy of produced components, surface flaws, accuracy of internal features, porosity, and material stress effects on dimensional stability.

Currently, metrological CT systems can perform successful measurements with sub-micrometer interpolated resolution of edge detection. Those measurements can be performed with accuracy better than $2\text{ }\mu\text{m}$. Figure 4, shows measurement deviation from a calibrated value of a distance between selected spheres. The artifact was calibrated using a scanning CMM and the uncertainty of this calibration was $1\text{ }\mu\text{m}$.

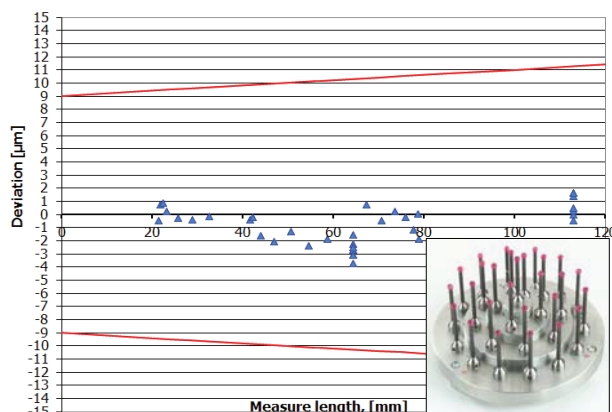


FIGURE 4. Metrological CT – Metrotom 1500 the accuracy of distance measurement between multiple spheres based on VDI/VDE 2630 standard. The horizontal axis show increments of 20 mm as a distance between spheres, and vertical axis shows $1\text{ }\mu\text{m}$ increments as deviation from calibrated distance between spheres using high accuracy CMM. Red lines define manufacturer specification.

Measurements of the artifact shown in Figure 1, were performed with Contura G2 coordinate measuring machine (CMM) equipped with Vast XXT scanning sensor with measurement accuracy stated by manufacturer as $1.8\text{ }\mu\text{m} + L/300$ (L – length in mm) and resolution of $0.2\text{ }\mu\text{m}$. Measurement of flatness was performed

along path shown as a yellow line on Fig. 2. Cylindricity of the central bore was measured by inspecting the profile at five different heights of the Center Bore from the bottom surface at: 3, 6, 9, 12, and 15mm.

Figure 5 shows a typical result of the flatness measurement. The flatness deviation is likely due to residual stress in the part and build platform causing warping. In fact, if the part is separated from the build platform (without heat treating), the residual stress state in the part changes and the warping is far more pronounced, as seen in Fig. 6. These large flatness deviations demonstrate the tremendous residual stress developed during many metal powder bed fusion processes.

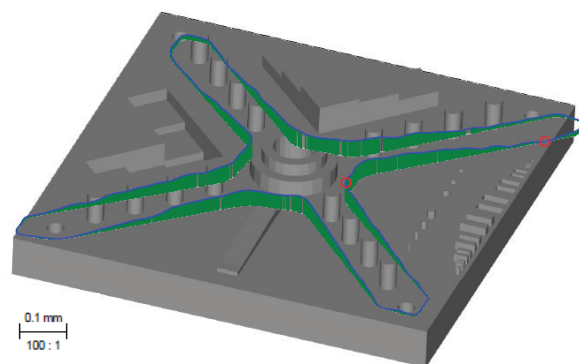


FIGURE 5. Evaluation of flatness of the artifact on the base plate right after build. The maximum deviation from inside to outside is 0.049 mm. The artifact was created by EOS M270 using 17-4 stainless steel.

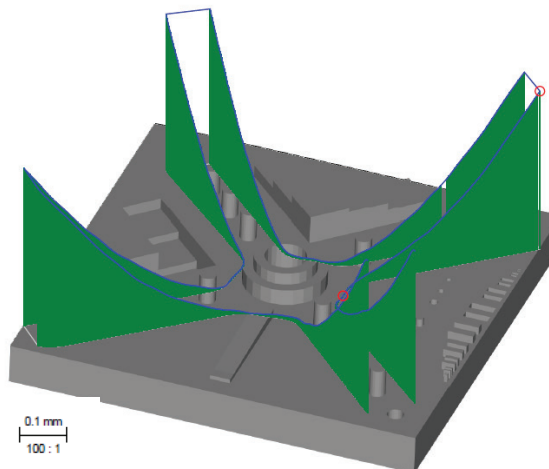


FIGURE 6. Evaluation of flatness of the artifact removed from the base using wire electrical discharge machining. The artifact was not heat treated. The maximum deviation from inside to outside is 0.498 mm.

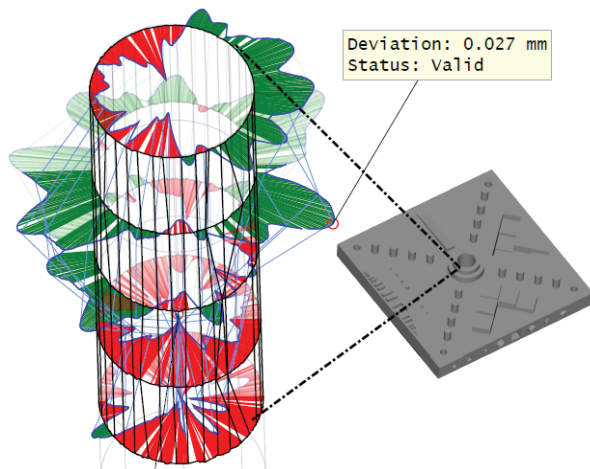


FIGURE 7. Cylindricity of the center hole right after build is 0.0531 mm.

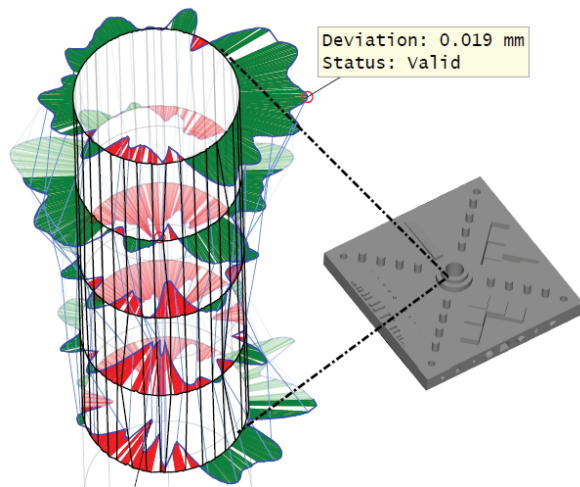


FIGURE 8. Cylindricity of the center hole after part was removed but not heat treated is 0.0457 mm.

Figure 7 shows a typical result of the cylindricity measurement. The maximum external deviation of 0.027 mm shows the expected tolerance this machine can expect to hold on a circular feature. Again, removing the part from the build platform changes the shape of the part, in this case resulting in better cylindricity.

The metrology carried out in this work provides important insights towards improving the fabricated lattice truss performance. The structure is intended for large volume patterning to retain part strength while reducing weight. This requires a repeatable lattice truss structure with minimal necking, breaks, warping or excess material. All of these error sources reduce the strength/weight ratio of the structure.

Repeat measurements of the same part shown in Fig. 9 indicate that the CT measurement error was on the scale of a few micrometers, well below that observed between parts or between the part and the design. This confirms that the CT measurements are able to capture the errors in the lattice truss structure.

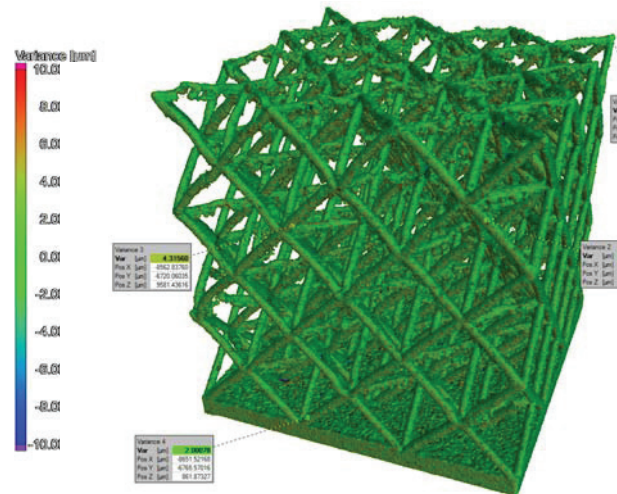


FIGURE 9. Repeatability map of 3 measurements. The measurements repeat with 4 μ m variance. CT data created by scanning the artifact with Zeiss Metrotom 1500 at 130kV, 225 μ A, and 29 μ m Voxel.

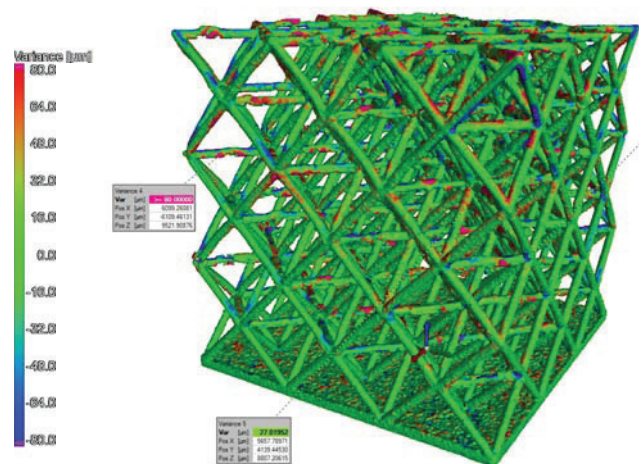


FIGURE 10. Reproducibility of the process between 2 same parts built by the M2 Cusing machine. The deviation exceed 100 μ m at certain locations. Same CT parameters as Figure 9.

The part-to-part variation comparison shown in Fig. 10 indicates that the fabrication process is anisotropic, which has been reported for laser sintering [2,3]. The largest variability ($\approx 100\mu$ m)

is mainly confined to the horizontal plane. This is significantly larger than the error observed on the angled off-horizontal struts. The part-to-part comparison also shows few large scale trends, meaning that the fabrication process is large scale repeatable and does not produce large warping variations between parts.

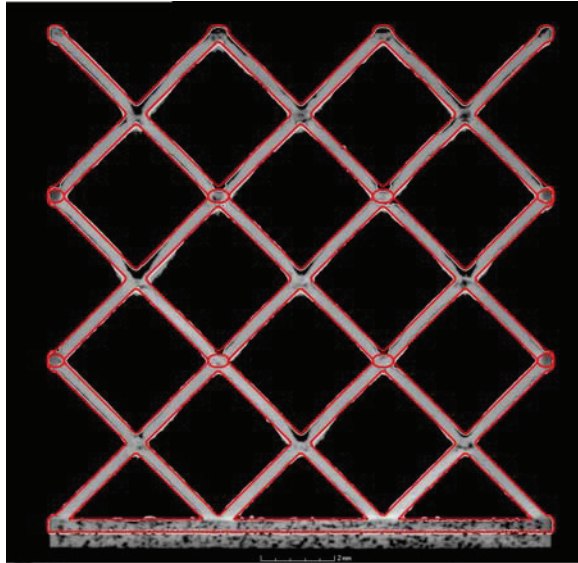


FIGURE 11. Side view – vertical cross section of the volume in Figure 3, showing typical deviations between the design (red line) and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

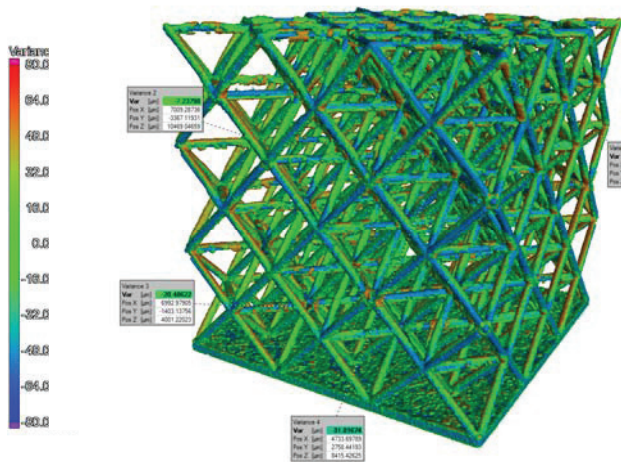


FIGURE 12. Typical deviations between the design and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

Several trends are visible in the absolute error of the part vs. the CAD model shown in Figs 11-14.

The angled struts often have small bends on their lower third, shown in Fig. 11, which would result in reduced buckling load capacity.

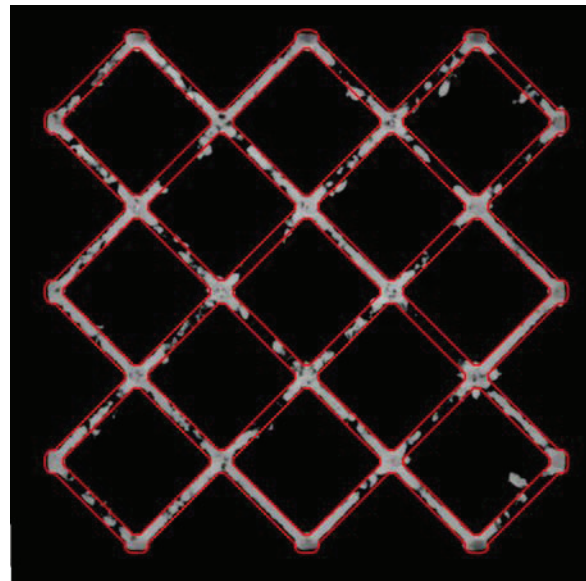


FIGURE 13. Top view - cross section of the volume in Figure 3, showing typical deviations between the design (red line) and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

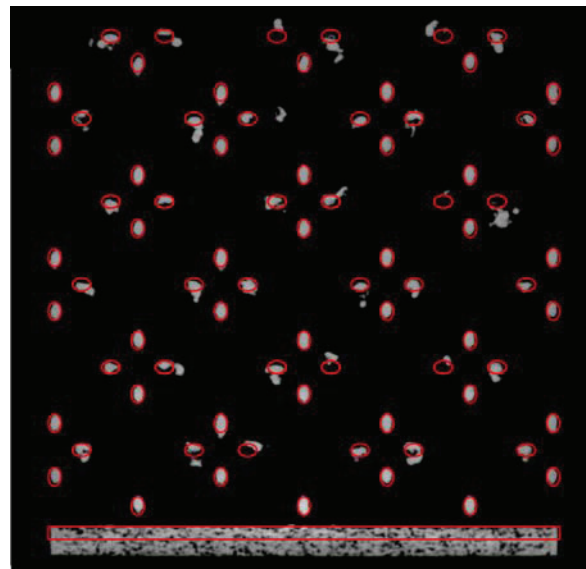


FIGURE 14. Node view - cross section of the volume in Figure 3, showing typical deviations between the design (red line) and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

The angling may be due to thermal effects at the vertex, and may be fixable by a slight increase in the structural mass above each vertex. The

parts show a trend of undersized struts in the corner facing the reader in Fig. 12. This is visible via the increasing blue seen in this area. The horizontal struts show an increased incidence of voids in Fig. 13, which reduces lattice truss strength. This appears to be a function of the fabrication process, and may be reduced by angling the part during fabrication. Finally, the cross-sections of the angled struts in Fig. 14 indicate that while most are in the correct location and size, the unwanted material does not form a Gaussian distribution around the desired area, but rather shows some significant outliers.

DISCUSSION

One of the difficulties in using test artifacts to characterize machine performance is that it is a post-process measurement. Because the part is removed from the AM machine before measurement, local datum features must be used to establish a local coordinate system and features can only be measured relative to each other (instead of relative to any machine datum surfaces). For the test artifact shown in Fig. 1, the top surface and the central hole are intended as primary and secondary datum features for measurement. The results shown here demonstrate the significant errors that can be present in these features. Using these as datum features may mask some of the deviations present and may transfer some of their deviations to the results of relative measurements of other features, confounding the ability to link specific deviations to specific machine/process sources. One might speculate that the build platform might be a better datum feature, but the build platform has no locating features in the x- and y-directions, and the platform is only aligned to the recoating blade to within 0.05 mm. Further, the building process starts with a layer of powder already atop the build platform.

The results of the CMM measurements also demonstrate the issue of when to measure the parts to best characterize the machine. It is easy to see that after the part is removed from the build platform, the shape is significantly different. However, it is difficult to say that these errors are fully the result of machine performance, especially if there is a heat treatment before removal. Measurement immediately after the part has been removed from the machine might give better correlation to machine performance, but since AM parts are

almost always post-processed in some way, these results may not be as indicative of an actual part's performance.

The CT metrology work shows that the lattice truss structures can be repeatably fabricated. It also aids in identifying several error trends which can be used for further part improvements, including location and general form of part variation as well as error. This knowledge can be used to both adjust the design and the fabrication process to improve the lattice truss strength and reliability.

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PROFICIENCY TESTING FOR INTERLABORATORY COMPARISONS ON INDUSTRIAL COMPUTED TOMOGRAPHY

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This paper discusses proficiency testing (PT) for inter-laboratory comparisons on industrial computed tomography (CT) measurements when the normalized error (E_n number) is used

as the statistical parameter to assess agreement between measured data, generally respect to a reference value. The results obtained in the analysis of such round robin tests should be interpreted with caution. To exemplify the case we take different sets of data coming from two recent CT comparisons [1, 2], and by scrutinizing some of their reported data we show how a laboratory can measure one parameter with large deviations from an assigned, or reference, value, but nevertheless be positively assessed ($|E_n| \leq 1$). Oppositely, some laboratories can receive an unsatisfactory performance ($|E_n| > 1$) even if their reported measurements are close to the assigned value. This happens when participants' reported estimates of measurement uncertainties are not determined in a consistent way. E_n -values not only provide a measure of how closely a reported laboratory result agrees with the assigned value (a reference), but also require uncertainty claims in both the laboratory result and the reference value. In that way, the normalized error value really gives a representative impression about the consistency of the results in regards to the claimed laboratory uncertainties. It is tempting then to review the uncertainty budgets from the industrial CT users. However, there is not yet a consistent approach to estimate uncertainty for dimensional measurements with CT machines due to the complexity of the physical phenomena involved collecting and analyzing data. A complete quantitative estimation of CT influencing factors is not available to guide development of a task-specific measurement uncertainty complying to the Guide to the

Expression of Uncertainty in Measurement (GUM) [3]. Additionally, there is currently a lack of standard procedures and guidelines for users of CT coordinate metrology.

ANALYSIS

To aid interpretation, the PT results are usually transformed into statistics that provide a performance judgment [4]. The usual statistics for PT performance assessment when participants are required to report the uncertainty estimates is the normalized error,

$$E_n = \frac{x - X}{\sqrt{U_{lab}^2 + U_{ref}^2}}, \quad (1)$$

where U_{lab} and U_{ref} are the expanded uncertainties associated with the participant measurement (or with its result x) and with the measurand (or the assigned value X), respectively. For a result to be *acceptable*, the E_n number must satisfy $|E_n| \leq 1$; *unsatisfactory* performance is obtained if $|E_n| > 1$.

Unsatisfactory results can be split into those caused by considerable errors in the measurement and those caused by an overly optimistic uncertainty estimate. An overly optimistic uncertainty estimate either means that some uncertainty contributions are underestimated or missed altogether, or that there are mathematical errors in the uncertainty budget, or something has happened to the measurement or the instrument that changes the deviations of measurements since the original testing when the uncertainty components were evaluated.

For the proficiency test to be valid, U_{lab} must contain all uncertainty components of importance for a given measurement. If U_{lab} is

underestimated, then it may lower the value of the denominator of equation (1), which increases the value for $|E_n|$ turning the performance criterion to register unsatisfactory of the measurement precision and process calibration. On the other hand, an overestimated uncertainty would produce a satisfactory result even if the deviations between the measurement and reference values are relatively large. Since overestimated U_{lab} values may reduce the $|E_n|$ and underestimated values may increase it, the use of the E_n metric to assess the performance would eventually lead to odd conclusions.

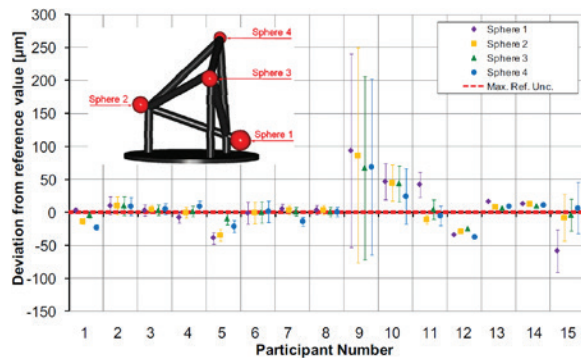


FIGURE 1. Measurement results for the diameters of a CT Tetrahedron (item 1) within the CT Audit comparison [1, 5].

For example participant 9 in Figure 1 overestimated U_{lab} and gets $|E_n| < 1$ (acceptable). The same happens with participants 13 and 20 on Figure 2. By other hand participants 6 and 7 (measuring sphere 4) in Figure 1 and 11 and 12 with precise measurements on Figure 2, underestimated their uncertainties, getting $|E_n| > 1$ (unsatisfactory). These conclusions can be drawn by direct calculation of equation (1) using the data gathered in the international inter-comparisons [1] and [2]. A plot of $|E_n|$ values for the measurements from Figure 2 is shown in Figure 3, where a pie chart (based on unfiltered data only) shows the participants performance based in E_n -criteria. If uncertainties cannot be estimated E_n -values cannot be calculated, and that is why there is a black portion in the pie charts in Figures 3, 5, and 7, to acknowledge data reported without an associated uncertainty

budget. Figure 5 shows an example in which 25 percent of the participants have not reported their uncertainty budgets on the measured data.

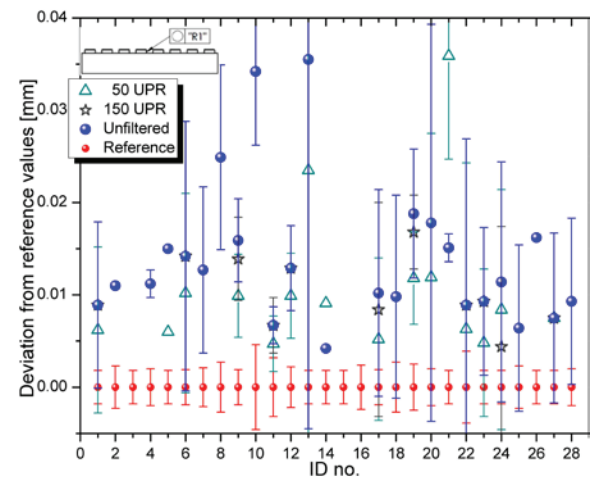


FIGURE 2. Measurement results for the roundness R1 of the inlet in polymer brick from LEGO (item 1) within the CT comparison [2].

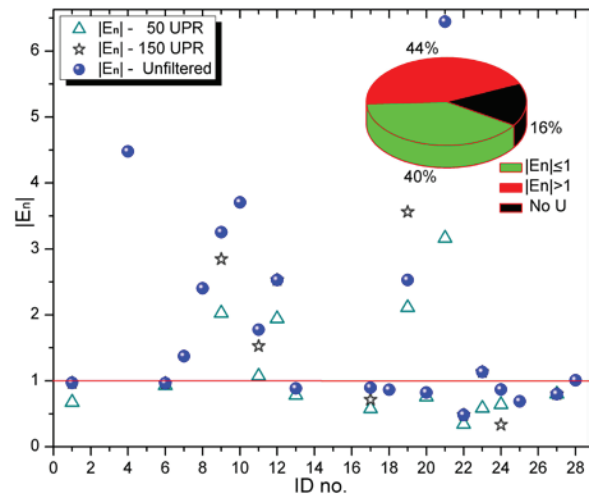


FIGURE 3. $|E_n|$ values for the data on Figure 2. $|E_n| \leq 1$ is satisfactory, $|E_n| > 1$ is unsatisfactory, and 'No U' refers to data reported without uncertainty statement. Pie chart is calculated from unfiltered data only.

Again, an analysis relying only on $|E_n|$ values as a criteria for performance assessment, may lead to counterintuitive conclusions. For example, from Figure 5 only 3 out of 24 participants reporting data measurements pass the assessment test ($|E_n| \leq 1$) for roundness measurements using CT machines; other participants may have gotten unsatisfactory

performance in their measurement process (six of them lacking an associated uncertainty budget). Notice that participant 17 in Figure 4 with the largest deviation from the reference value gets positively assessed in Figure 5. This is because participant 17 reported a correspondingly large uncertainty associated with the measurement. Now, when the reference value is very precise (with very low uncertainty), participants with low estimates on the uncertainties associated to their reported measurements take the risk of being negatively assessed no matter the accuracy of the measurements, which is the case of participants 9, 11, 19, and 23 with measurements close to the reference values on Figure 4. Because of their low reported uncertainties, eq. (1) makes their corresponding E_n -numbers fall behind the critical value $|E_n| = 1$, see Figure 5. This may be seen as unfair for some participants in PT inter-comparison schemes, but that is the way the E_n -number works.

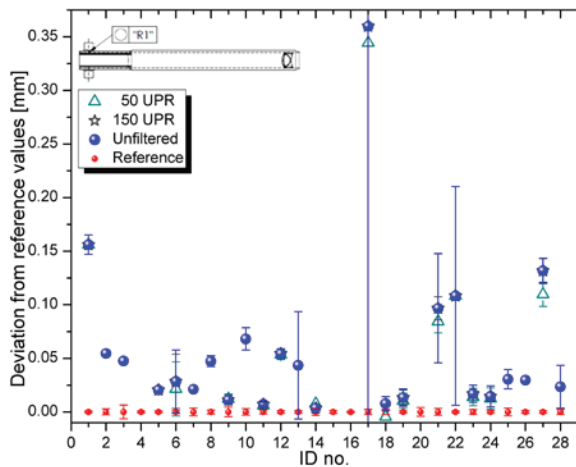


FIGURE 4. Results for roundness $R1$ measurements on a metallic tubular component (item 2) in the CT comparison [2].

E_n -values are parameters to include both the laboratory bias ($x - X$) and the laboratory claimed uncertainty U_{lab} . Indeed, this metric provides a measure of how closely a reported participant measurement agrees with the reference, taking into account the uncertainties of both the participant result and the reference value. The assumption is then made that all the reference measurements are metrologically traceable and have associated uncertainties soundly established and sufficiently small. The

precision and traceability of the assigned values or reference measurements for CT comparisons can be established by using tactile coordinate measuring machines (CMMs). Furthermore stability of the items under study can be verified through comparison of those measurements before and after the circulation time period between participants. Reference values for the measurands of the CT studies cited here were established and documented by the coordinators of those studies [1, 2, and 6].

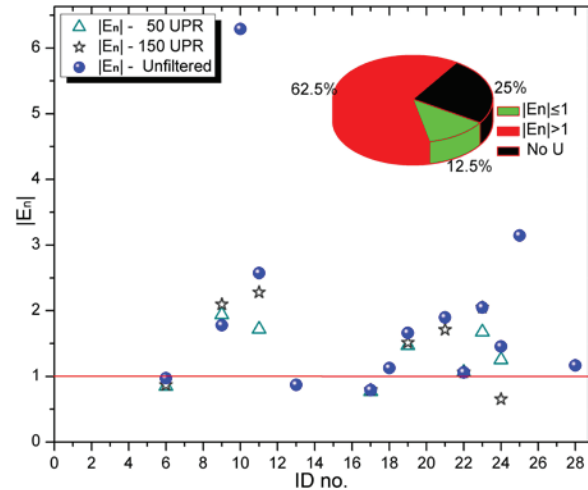


FIGURE 5. $|E_n|$ scores for the measurements on Figure 4. $|E_n| \leq 1$ is satisfactory, $|E_n| > 1$ is unsatisfactory, and 'No U' refers to data reported without uncertainty statement. Pie chart is based on unfiltered data only.

According to the ISO/IEC 17043:2010(E): if scores consider the participants' reported estimates of measurement uncertainty (which is the case for E_n -values), these will only be meaningful if the uncertainty estimates are determined in a consistent manner by all participants, such as in accordance with the principles in ISO/IEC Guide 98-3 [7]. With the current state-of-art for industrial CT technology, dimensional measurements are still facing difficulties in the evaluation of their uncertainties because of challenges in both identifying and quantifying all error sources for a process with such complexity and multiple influencing factors as it is for CT. There is not yet an available guide to make quantitative estimations of measurement uncertainties for CT following the GUM requirements [3, 7]. Figures 1, 2, and 4, are clear examples of CT dimensional measurements with a non-uniform consistency

in the reported uncertainties from the participants. The quality of those uncertainty estimates, which is variable, leads to counterintuitive conclusions about performance assessment of results based in the E_n parameter, as it has been already mentioned through this paper with some specific examples. Two of the main factors that increase the variability in uncertainty estimates within inter-comparisons tests are the operator influence and the accuracy of the CT measurement machines. In the case of the CT inter-laboratory comparisons mentioned above, this is evidenced by the fact that non-measuring oriented CT systems were included as part of a study focused in evaluation of dimensional metrology performance [8, 9].

To enable judgment as to whether the uncertainty estimates are reasonable or not, $|E_n|$ values illustrate the importance of reporting realistic uncertainties. $|E_n| < 1$ is always satisfied when U_{lab} is chosen deliberately large. Oppositely, very small U_{lab} values can easily lead to $|E_n| > 1$. To summarize, when using the normalized error (E_n number) as the statistical parameter to assess performance in a PT, we should be aware of the following possible events:

- Uncertainty *overestimated*: $|E_n|$ is significantly less than 1
- Uncertainty is *consistent*: $|E_n|$ typically falls in the range 0 to 1
- Uncertainty *underestimated*: $|E_n|$ is bigger than 1

From equation (1), scoring $|E_n| < 1$ (*satisfactory performance*) still depends on quantity $(x - X)$, which is called the '*estimate of laboratory bias*' in ISO 5725-4 [10]. This simple difference, may be adequate enough to determine performance according to ISO/IEC 17043:2010(E) [4], and it is precisely the deviation of reference plotted in Figures 1, 2 and 4. This is the statistical parameter more easily understood by participants and performance can be easily read directly from its plots, offering thus a quick alternative when reported uncertainties are not

consistently determined by all the participants. The estimate of laboratory bias is certainly very useful when testing emerging new technologies where uncertainty estimates are very difficult to do as it is for industrial CT metrology.

Let us analyze in detail one more example, this time data in which reported uncertainties seems to show more uniformity between participants than the examples exposed already. See Figure 6, which corresponds to CT data coming from the inter-laboratory study [2]. The performance based in $|E_n|$ values for that case can be found in Figure 7. We see only about 23% of the participants failing the PT based in the $|E_n|$ criteria this time, lesser than the percentage of participants failing the PT in the other examples previously discussed here (Figures 3 and 5). With the distinctions made so far, the three possible events listed above are apparent. Participant 27 overestimates its uncertainty, $U_{lab(27)} = 0.1072$ mm, getting $|E_{27}| = 0.0326$, significantly less than 1. Participant 25 also gets normalized error value very small, $|E_{25}| = 0.1839$, but without overestimating the uncertainty, $U_{lab(25)} = 0.0080$ mm. What makes $|E_n|$ small in this case is the low measurement deviation from the reference $(x - X)_{25} = -0.0005$ mm, the smallest lab bias reported by any participant in the dataset from Figure 6. A similar situation happens with participants 1, 7, 12, 18, and 20. Moderate uncertainties are reported by participants 9 and 11, $U_{lab(9)} = 0.0046$ mm and $U_{lab(11)} = 0.0020$ mm, with also small laboratory bias $(x - X)_9 = -0.0016$ mm and $(x - X)_{11} = -0.0020$ mm, getting $|E_9| = 0.3111$ and $|E_{11}| = 0.6897$ respectively; which are values in the range 0 to 1. An underestimate uncertainty is reported by participant 19, $U_{lab(19)} = 0.0001$ mm, whom with a quite precise measurement $(x - X)_{19} = 0.0012$ mm, gets negatively assessed, $|E_{11}| = 1.0909 > 1$. Two laboratories that estimated small uncertainties but laboratory bias relatively larger

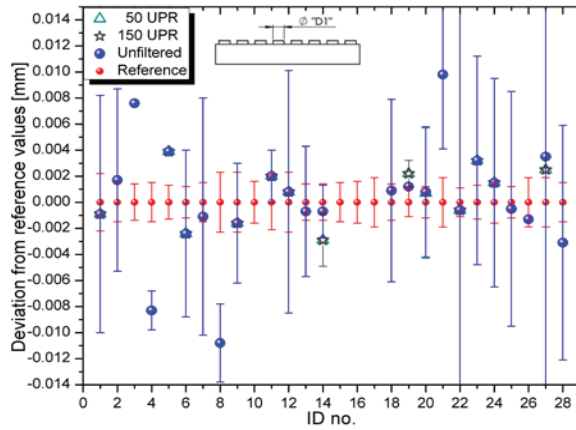


FIGURE 6. Results for diameter $D1$ of the inlet in polymer brick from LEGO (item 1) within the CT comparison [2].

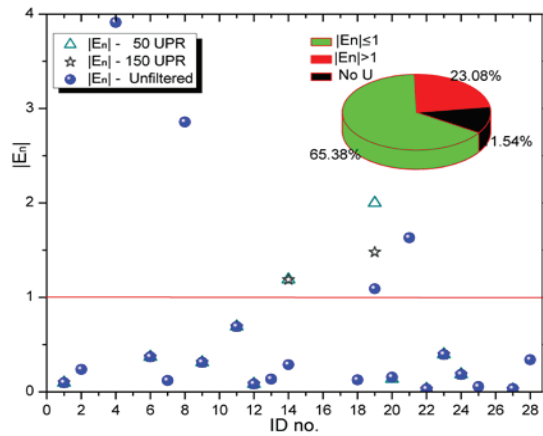


FIGURE 7. $|E_n|$ values for the diameter measurements on Figure 5. E_n -criteria: $|E_n| \leq 1$ is satisfactory, $|E_n| > 1$ is unsatisfactory, and 'No U' refers to data reported without uncertainty statement. Pie chart is based on unfiltered data only.

are 4 and 8 (see Figure 6), with $U_{lab(4)} = 0.0015$ mm and $U_{lab(8)} = 0.0030$ mm, and $(x-X)_4 = -0.0083$ mm and $(x-X)_8 = -0.0108$ mm, obtaining $|E_n|$ values considerable larger than 1, $|E_4| = 3.9127$ and $|E_8| = 2.8570$, and hence they are assessed negatively as should be expected for measurements reported with uncertainties

similar or lower than the reference uncertainties ($\overline{U_{ref}} = 0.0016$ mm) but located more than two $|\overline{U_{ref}}|$ apart from the reference, $(x-X)_4 \approx -5.2|\overline{U_{ref}}|$ and $(x-X)_8 \approx -6.8|\overline{U_{ref}}|$.

As has been noted before, the data in Figure 6 seems to report uncertainty budgets in a more uniformly way than Figures 2 and 4, and that is why in this case the $|E_n|$ -criteria to determine performance assessment for the participants of the round robin test provides a more reasonable comparison as would be expected. Thereby, for these kinds of inter-comparisons, the key factor to verify before to make an evaluation of performance results based in the E_n parameter appears to be the consistency in the reported uncertainties. Accordingly, we should have caution in the interpretation of $|E_n|$ when it is suspected that the uncertainties reported by participants were not estimated in a uniform and consistent way following the GUM requirements [3] or a similar approach. An evaluation of performance based on laboratory bias $(x - X)$ calculations may be preferable in those cases. Calling back the improved uniformity in the reported uncertainties for Figure 6 compared with Figures 2 and 4, it is noted that it does not just happens by coincidence, but as consequence of the fact that in CT metrology errors of form measurement are more affected by the segmentation and surface determination parameters than center positions and distance measurements [11], making uncertainties expected with roundness measurements more variable and larger than uncertainties associates to distances, i.e. uncertainties are a function of form.

CONCLUSIONS

The use of the normalized error (E_n) for performance assessment of PT does not fully reflect the precision and calibration of a process. Specifically, an overly large uncertainty estimate with a measurement process of relatively poor precision will be more highly rated than a very precise process carefully calibrated for which a relatively small error in uncertainty places the error bar beyond the reference value. A small error in a carefully evaluated process has more impact than a relatively large error for overly

conservatively estimated uncertainties. This is observed in measurements representing the current state of the art of CT metrology. We should use caution in the interpretation of $|E_n|$ when uncertainties reported by participants were not estimated in a uniform and consistent way following the GUM requirements or a similar approach. For the PT performance assessment to be valid, U_{lab} must contain all uncertainty contributors of importance in the given situation. $|E_n|$ -scores only provide objective evaluation when consistency with the definition of expanded uncertainty given in the GUM is provided. However, incorporating the participants reported uncertainties within PT schemes, and the information about how those were obtained, plays an important role in understanding metrology issues, especially in emerging new technologies. In the case of industrial CT it is desirable to determine a precise and traceable way to predict uncertainties, mainly due to the phenomenological complexity of the measurement setup and the large amount of still unquantifiable influencing factors adding to uncertainties. Even though uncertainty budgets are difficult to estimate, the inter-laboratory comparisons still have value for industrial CT because they offer an opportunity to increase understanding of quality issues in CT dimensional metrology and to determine possible reasons for variations. One of the challenges is to assemble a database of sources of uncertainty for industrial CT user to enable better estimation of U_{lab} in metrological measurements.

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Understanding Error Generation in Fused Deposition Modeling

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INTRODUCTION

Additive Manufacturing (AM) can improve flexibility and convenience, lower manufacturing costs, and reduce time to market for many manufacturing applications [1,2]. Successfully implementing and expanding AM requires improvements in surface quality, shear and tensile strength, build time, accuracy, and precision of these processes [3]. Of these issues, surface quality, accuracy, and precision are the biggest obstacles preventing AM from becoming a primary production process [4]. This paper aims to understand the relationship between process characteristics and error generation in Fused Deposition Modeling (FDM), which is an AM process typically used for prototyping. Understanding error generation can improve the scalability of AM technologies and expand their use to create better products.

BACKGROUND

The major sources of error in the positional accuracy of the drop deposition of rapid prototyping systems, such as FDM, include mathematical errors due to the approximation of part surfaces in the standard file input; process-related errors such as positioning errors in the xy plane due to translation of the printer head and in the z-axis due to the registration of different layers; and material-related errors, such as shrinkage, distortion, and seepage of binder during production [5]. The accuracy of the printing process also depends on errors generated by each machine component. This paper primarily focuses on examining process- and machine-related errors.

The process characteristics that limit the accuracy of AM techniques, such as FDM,

include the layer thickness, build orientation, raster angle, air gap, and raster width [3,5]. Of these, the build orientation has been found to be a primary influence on the dimensional accuracy, surface roughness, shear and tensile strength, build time, required support structures, and cost of FDM parts [4,6]. The layer thickness and overlap interval between fibers also affects the surface roughness of printed parts [7]. This effect is due to the “staircase effect” in FDM processes. When FDM machines deposit beads of material layer by layer, a staircase-like structure is formed on inclined or rounded features, which increases surface roughness.

Examining the effect of FDM process parameters on part quality has been primarily accomplished using developed control parts. Clemon et al. [8] measured the quality of a control part printed using FDM and photopolymer jetting. Feature completion and dimensional accuracy were the main measures of part quality. They measured the smallest gap width of a printed slot feature and determined that the minimum resolution of the studied machines varied from 0.4 to 0.6 mm. Upcraft and Fletcher [9] analyzed the dimensional accuracy of several AM techniques, including FDM. They found that none of the processes were capable of achieving dimensional accuracy greater than 97.8%.

Other studies have developed techniques to improve the accuracy of FDM. One example of error compensation is the use of an optimal shrinkage compensation factor (SCF) [10,11]. A disadvantage of the SCF is that only one compensation factor is used for all directions and it only applies for homogeneous deviations.

Any approach to improve the accuracy of FDM must be based on a reliable characterization of error in the process. Thus, the goal of this paper is to identify process- and machine-related error sources in FDM so that a framework that characterizes error in an FDM machine may be developed using an error budget approach.

IDENTIFYING ERROR SOURCES IN FDM

This research first examined how the build orientation and part density affected the form and resolution of FDM parts. Six control parts (Figure 1) were manufactured on two FDM machines: Stratasys Dimension BST 1200es and SST 1200es. These FDM machines have a minimum layer thickness of 0.254 mm and produce parts made from “ABSplus,” which has similar mechanical properties to acrylonitrile butadiene styrene (ABS) [12]. The control parts were printed with two different density settings from each machine: solid and low density. All other parameters were kept constant.

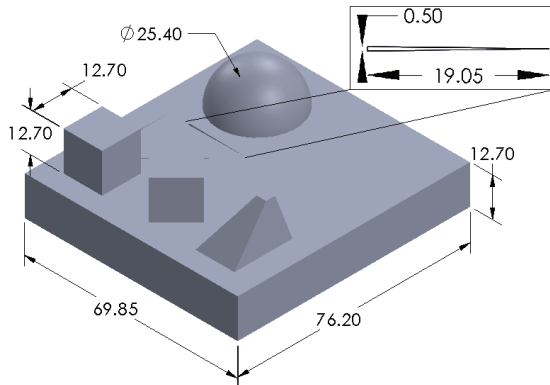


FIGURE 1. Control part #1 used to quantify form errors and resolution in FDM (all units in [mm]).

An Olympus SZ optical microscope was used to measure the form and resolution of the control part. Form was evaluated using the measured roundness of the hemisphere feature and qualitative observations of the printed part. Resolution was estimated from the length and minimum width of the tear drop feature.

To investigate the influence of the staircase effect on the surface roughness, another control part (Figure 2) was designed with surfaces that varied the build orientation (θ) from $0^\circ \leq \theta \leq 90^\circ$ in intervals of 5° . The surface roughness R_a of each surface was measured using a MarSurf M1 stylus tip profilometer along the measurement path delineated in Figure 2. This profilometer

had a tip radius of $2.5 \mu\text{m}$ and profile resolution of 12 nm.

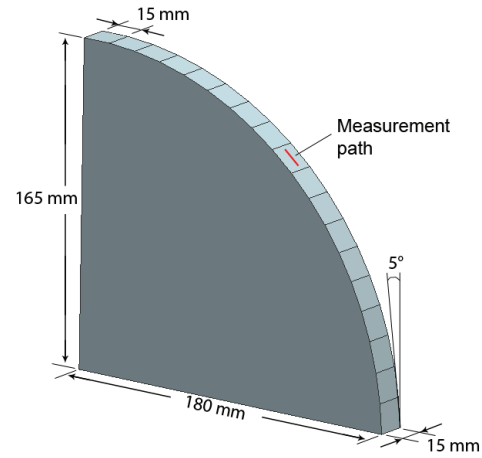


FIGURE 2. Control part #2 used to investigate the staircase effect on surface roughness.

To quantify accuracy and precision across the entire work volume, the control part shown in Figure 3 was printed on the Stratasys Dimension SST 1200es. This control part was measured with a coordinate measuring machine with a scanning head of 6 mm diameter. The actual position of each corner point was identified as the intersection of the three adjoining planes, which were located by approximating best-fit planes using ~ 400 measured points on each surface. The root mean square (RMS) deviation between the actual and nominal position of each corner point represented the accuracy at each position in a specific direction (Equation 1). The precision was represented by the extended interquartile range IQR_{ext} , which contained 90% of all measurement points at a specific position.

$$RMS_x = \sqrt{\frac{(x_1^{act} - x_1^{nom})^2 + \dots + (x_n^{act} - x_n^{nom})^2}{n}} \quad (1)$$

Results

Figure 4 shows the observed form error in control part #1 (Figure 1); it indicates gaps where material was not deposited. Roundness was estimated by examining the second deposition layer from the top of the hemisphere and drawing the smallest circle that would enclose the layer and the largest circle that would reside within the layer. The difference between the two radii was calculated and is shown in Table 1.

The resolution was estimated by first identifying the tip of the printed tear drop feature. The

length of the tear drop features was significantly smaller than the desired length: the average length was 13.9 mm versus the average desired length of 19.1 mm. The expected width of the tear drop feature at its printed tip was then used as the resolution estimate. Table 2 shows the calculated average minimum resolution in the x, y, and xy directions for both FDM machines studied in this paper.

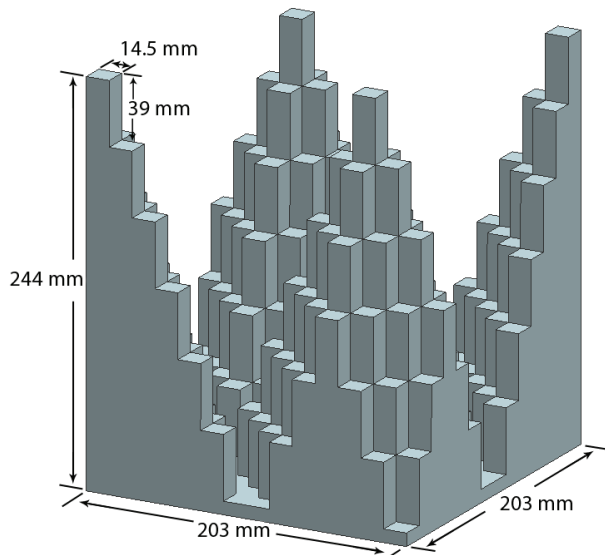


FIGURE 1. Control part #3 used to estimate the accuracy and precision of FDM.

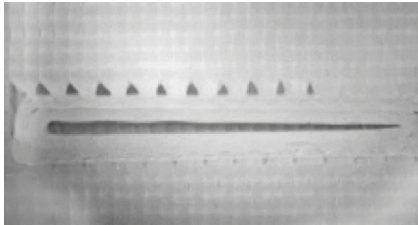


FIGURE 4. Form error observed in control part #1.

TABLE 1. Roundness error of the SST and BST control parts [mm].

Machine	Density	Radius Difference [mm]
SST	Solid	0.272
SST	Low	0.215
BST	Solid	0.438
BST	Low	0.313

Figure 5 shows the surface roughness of each face measured on control part #2. It illustrates the anticipated increase in surface quality that occurs when the build orientation increases over the range $45^\circ \leq \theta \leq 90^\circ$.

TABLE 2. Average minimum resolution of the SST and BST control parts [mm].

Machine	Density	Avg Min Resolution [mm]
SST	Solid	0.143
SST	Low	0.130
BST	Solid	0.128
BST	Low	0.126

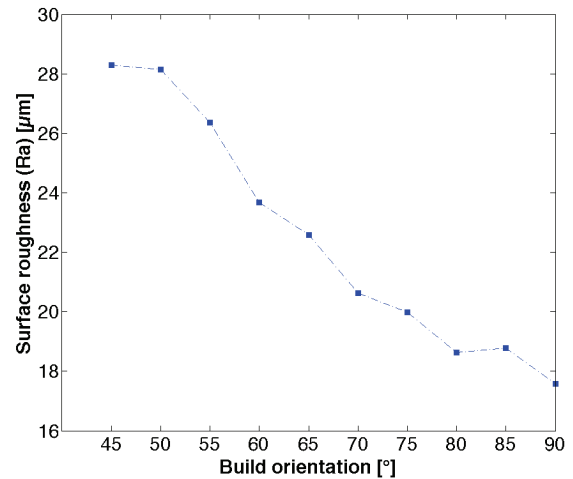


FIGURE 5. The relationship between surface roughness and build orientation for control part #2.

Table 4 shows the estimated accuracy based on the measurement of control part #3. Accuracy with respect to the y direction is greater than that with respect to the x direction. This could have been caused by the axis configuration. Since the y axis carries the x axis, the error in the x direction could have been additionally influenced by the error in the y axis.

TABLE 3. Comparison of achievable accuracy for deviations in x, y, and z directions.

Direction	Lower Limit	Upper Limit
x	0.12 mm	0.62 mm
y	0.08 mm	0.30 mm
z	0.21 mm	0.57 mm

Table 4 summarizes the estimated precision based on the measurement of control part #3 for the x, y, and z directions, respectively, with respect to different positions. Generally, the z direction has the greatest precision for the FDM machine in this study.

TABLE 4. Comparisons of precision in the x, y, and z directions with respect to different x, y, and z positions.

	X Direction		Y Direction		Z Direction	
	IQR _{ext} [mm]		IQR _{ext} [mm]		IQR _{ext} [mm]	
	Min.	Max.	Min.	Max.	Min.	Max.
X Position	0.32	0.71	0.26	0.70	0.26	0.51
Y Position	0.21	0.89	0.12	0.59	0.17	0.41
Z Position	0.23	0.58	0.27	0.90	0.19	0.24

CHARACTERIZING ERROR IN FDM

The second part of this research focused on a framework to characterize and quantify error in the FDM process. This was completed by developing an error budget for the Stratasys Dimension SST 1200es.

The axis configuration of the considered FDM machine was described as *w-Z-f-Y-X-t*, where the identified machine components are the workpiece *w*, the z axis, the fixed machine foundation *f*, the tool *t*, the x axis, and the y axis, which is also based on the fixed machine foundation. The parametric error components of the three linear axes have to be included in the mathematical error model. Every linear axis had six component deviations (scale error, two straightness errors, roll, pitch, and yaw) and three position deviations (deviation of the initial position and two squareness errors with respect to the other axes). Therefore, the total number of error components considered should have been 27 [13]. But, by defining the coordinate system of a machine tool, its zero position deviations and three of its squareness errors were set to zero. This meant that the FDM required 21 error components since it has three linear axes.

Homogeneous Transformation Matrices (HTMs) were used to transform the coordinates and errors of one component to the coordinate system of another component. Generating two HTMs that represented the location of the nozzle tip and a desired location on the workpiece, respectively, relative to the fixed machine foundation captured the influence of all error components with respect to the reference frame. The general HTM for the transformation of a linear axis with coordinate system *J* into coordinate system *I* is shown in Equation 2, where δ represents translational errors, ϵ represents rotational errors, and *a*, *b*, and *c* are offsets between the different coordinate systems in x, y, and z direction, respectively. The deviation between the nozzle tip and workpiece location was a measure of the process error.

$$T_{IJ} = \begin{bmatrix} 1 & -\epsilon_x(j) & \epsilon_y(j) & a_j + \delta_x(j) \\ \epsilon_z(j) & 1 & -\epsilon_x(j) & b_j + \delta_y(j) \\ -\epsilon_y(j) & \epsilon_x(j) & 1 & c_j + \delta_z(j) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Because the FDM machines used in this study provided less direct control of each axis, the use of standard experiments to determine the error components was not feasible. Instead, each error component was approximated using a Legendre polynomial P_j (Equation 3) [14]. Thus, approximating error component required calculating the polynomial coefficients a_i . But, this approximation makes it impossible to differentiate between the scale and squareness errors of an axis. Therefore, the FDM machine was assumed to be an orthogonal system [15], and the number of considered error components was reduced to 18.

$$\delta_x(x) = \sum_{i=0}^n a_i \cdot P^i(x) \quad (3)$$

The mathematical model was implemented as a least squares problem in MATLAB®. This approach required data from a minimum of 54 features to determine 21 error components with three polynomial coefficients each (this was the motivation for the design of control part #3). The number of features actually generated in control part #3 was greater than the minimum needed, though, to create an overdetermined system of equations that would have minimized the influence of nonrepeatable error terms and allow for a more accurate approximation of the error components. In addition to the error components, the error gains (or offsets between the origins of each component coordinate system) were measured.

Results

The results of the error budget demonstrate the approximated propagation of the translational and rotational error components of each linear axis. Selected results are shown in Figures 6, which display the translational error components of the y axis. Generally, it was determined that third order Legendre polynomials, which have been used primarily in literature [16,17], have greater approximation error than second order Legendre polynomials.

By using the second order approximation, it was determined that among the translational error components, the main contributors to the error of the machine tool are: the straightness error of the x axis in the z direction, the straightness

error of the y axis in the x direction, and the straightness error of the y axis in the z direction, with maximal values in the range of 0.011 - 0.014 mm. The scale errors of the three axes were investigated to be less. Among the rotational error components, it was identified that the yaw of the z axis with a maximal value of ~600 arc seconds is the main contributor to the overall machine error. Thus, the rotational errors of the x and y axes could be neglected during first improvement attempts.

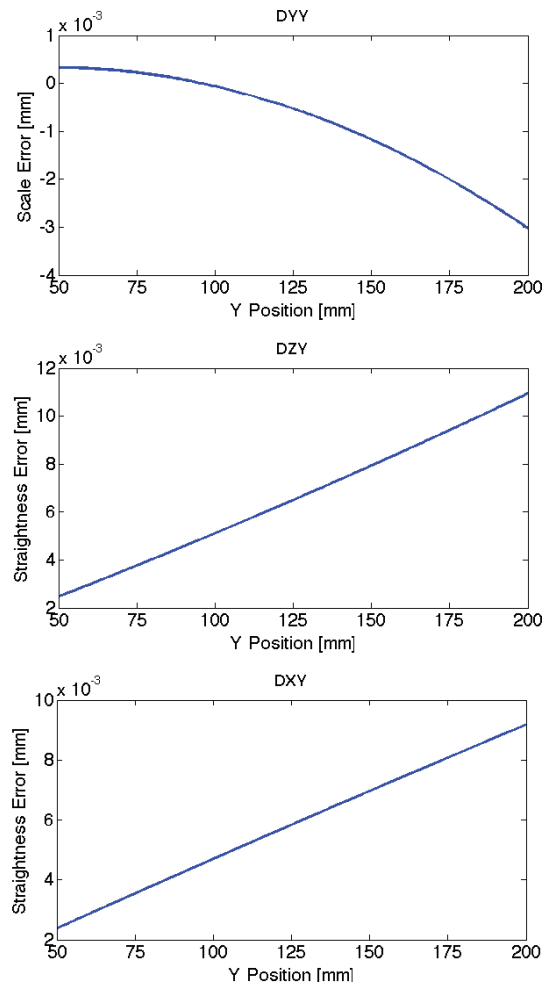


FIGURE 6. *Approximated translational error components of the y axis.*

CONCLUSION AND FUTURE WORK

The goal of this paper was to understand how process characteristics influenced error generation in FDM. Different sources of error were identified by focusing on the effect of build orientation and part density on form, resolution, and surface roughness. Control parts were utilized to quantify these errors. Accuracy and precision were estimated across a large portion

of the work volume, and these results informed the development of an error budget framework for FDM that can help characterize the error expected in the process.

The presented work did have some limitations that should be addressed in future work. For example, control part #1 did not cover the entire printable area of the machine, which means that some of the observed errors could have been different if the control part were located on a different part of the printing bed. Also, determining the overall accuracy and precision for the examined FDM machine tool was not possible. The common procedure to determine each error component was not feasible due to limited control of axis motion and process parameters as well as an inability to clamp measurement equipment to the FDM machine. Thus, the component errors could only be approximated. Additional sources of error could have also existed that contributed nonrepeatable errors that were assumed to be zero in the error model. Finally, material behavior was a major error source that was not considered because of its unclear impact on the error budget. Therefore, the results presented likely had some modeling error.

Future work will seek to use FDM machines that provide control of additional process parameters. Furthermore, the accuracy of approximations using the error budget will be improved by considering additional sources of error since the current model only considers the component deviations of the machine tool as sources of error. Process errors and errors caused by material behavior will also be considered since they are expected to be significant. Finally, further validation of the approximated error components in this study will be conducted to better quantify modeling error.

The work presented in this paper illustrates the current limitations of FDM by contributing to an understanding of error generation. The results of this work can be used to identify possible process improvements in the design and control of FDM technology. Ultimately, these types of innovations are necessary for AM to be more widely accepted in industry.

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PERFORMANCE VERIFICATION OF 3D PRINTERS

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INTRODUCTION

During the last decade additive manufacturing processes have multiplied and evolved from mere prototyping towards true production. Furthermore, the last five years have shown an exponential growth in small table-top machines that can be acquired for a limited cost. One of the challenges of this development is to make sure that the 3D printers actually produce parts according to specifications. This is a big issue when producing complex parts with internal features as illustrated in [1]. However, a basic requirement for making all sorts of parts within specifications is that the machine tool as such (i.e. the 3D printer) is calibrated. This paper proposes a method to verify and possibly optimize the performance of a 3D printer by printing an artefact which is then subsequently analyzed. Based on these findings a possible correction of positioning errors and squareness errors can be applied, see Figure 1.

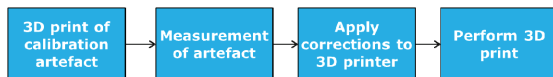


FIGURE 1. Illustration of proposed approach.

APPROACH

The approach is based on the application of a calibration artefact for coordinate measuring machines (CMMs) called the optomechanical hole plate, see Figure 2. The hole plate was developed to create a connection between the traditional calibration method of mechanical CMMs and CMMs equipped with optical probes. The hole plate can be calibrated using a reversal method [2] and subsequently used to verify the performance of other CMMs [3,4].

In this context the design of the hole plate has been used because it is possible to measure this geometry with an acceptable accuracy on standard CMMs. 3D printed hole plates were produced with 25 holes (5x5) with a nominal diameter of 5,5 mm and a nominal center

distance of 20 mm in both X and Y directions. The thickness of the printed 3D hole plate is selected to 5 mm making the plate rigid.

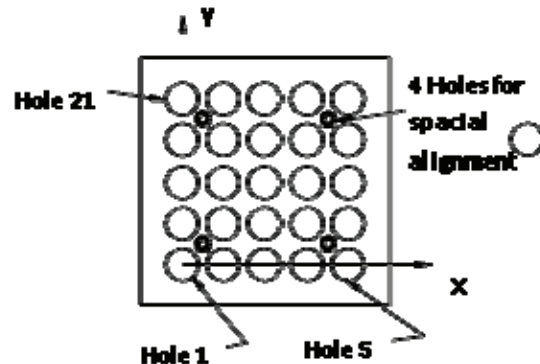


FIGURE 2. Illustration of principle of hole plate layout.

In this investigation a FDM based commercially available 3D printer was used and the material was ABS: The ABS filament is extruded through a nozzle at 260 °C. The diameter of the raw filament is Ø1.75 mm and the extruded filament is approximately Ø0.5 mm. The nozzle is moved using a CNC control in a Cartesian coordinate system.

INITIAL RESULTS

The 3D printed hole plates were measured using a mechanical CMM and the data analyzed. Centre coordinates of the 25 holes were determined and the length between these calculated. Deviations from nominal (and expected) lengths were plotted (Figure 3 – X and Y directions only). Based on this correction values can be estimated and applied. It can be seen from the bottom part of Figure 3 that the perpendicularity error is almost negligible compared to the scaling errors.

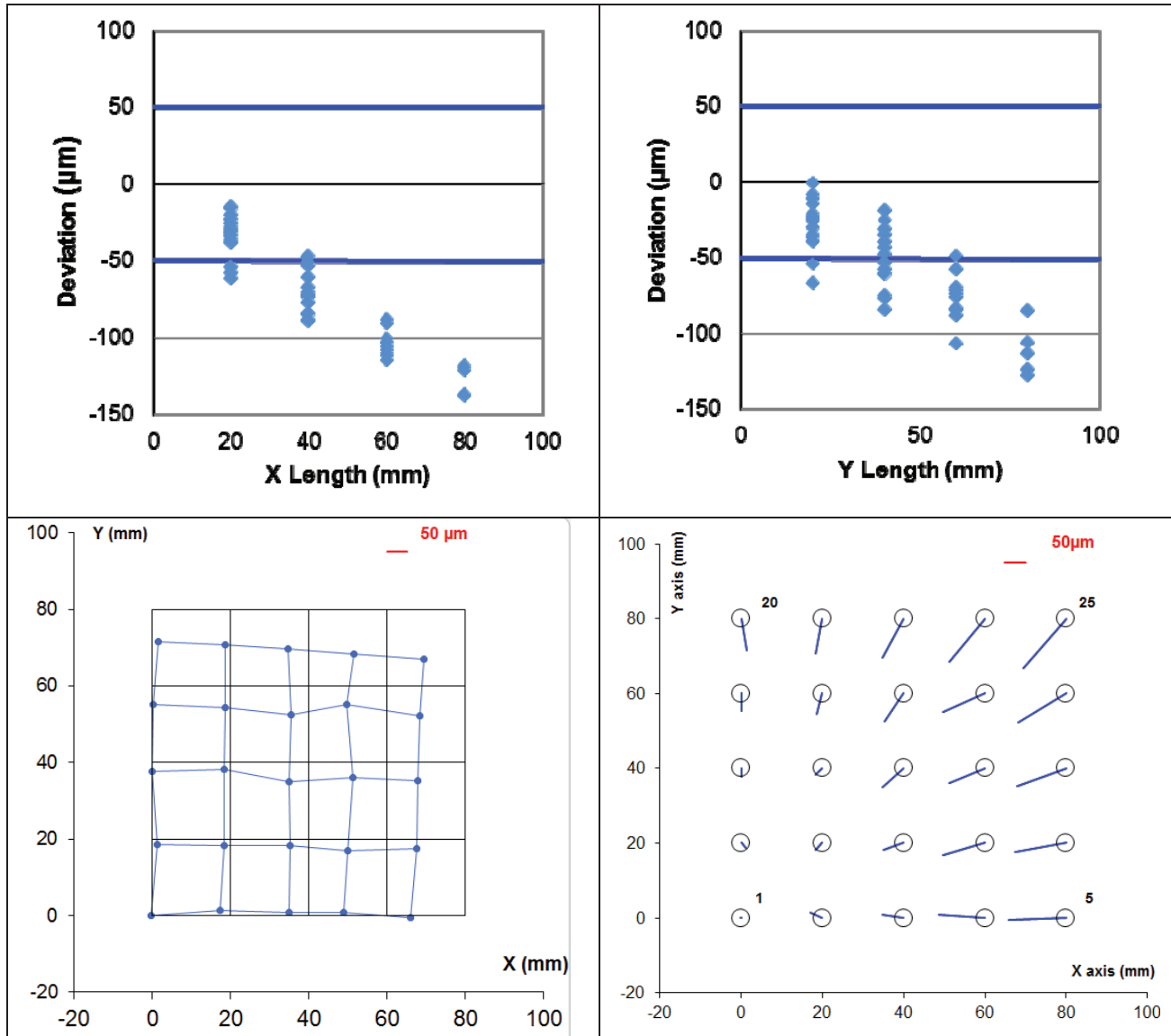


FIGURE 3. Analysis of 3D printed hole plate. Deviations from nominal position (bottom) and deviations from nominal length (top).

ANALYSIS OF MEASUREMENT UNCERTAINTY

It is clear from Figure 3 that there are scale errors that should be corrected. Also dispersions of points on length between center coordinates indicate variability in the determination of the center coordinates. This is due to the fact that the FDM process will create a layer-based component and this is also the case in the holes. An analysis of this phenomenon and its implications on the approach was performed.

Roundness of the printed holes was analyzed by means of a mechanical CMM. A standard approach to the measurement of a high quality hole plate in steel is based on determination of center coordinates by means of a 4 point measurement [3,4]. Figure 4 shows the progression of roundness of one printed hole as a function of measurement points. It is clear that the printed holes are not optimal for measurement purposes. A 4 point measurement clearly underestimates the roundness error by approximately 40 μm. It seems plausible that the roundness error of a single hole is of the order of

60 μm with variations up to 100 μm . The roundness error also is depending on the Z-height at which the measurement is performed. The large variation is an indication of this phenomenon. Figure 5 illustrates roundness deviations of selected holes.

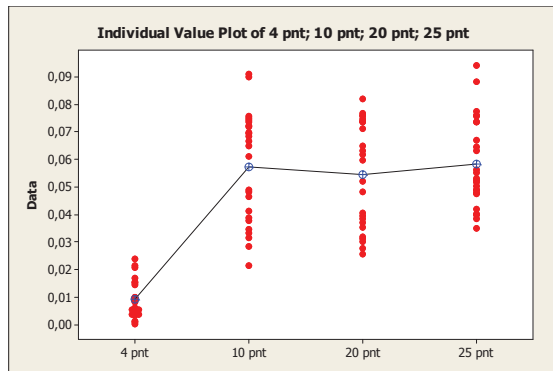


FIGURE 4. Roundness of printed hole as a function of measurement points. Vertical scale shows roundness error in [mm]. Measurements performed using a mechanical CMM with a probe of $\varnothing 2\text{mm}$.

The layered nature of the printed part is illustrated in Figure 6. Here mechanical roughness measurements were performed along a generating line of the inside of the hole. It is seen from Figure 6 that the layer thickness is of the order of 250 μm . It can also be seen that the stylus is not able to reach the bottom of the profile. However, the variation of the top position of the profile varies, and this will affect the roundness measurement as well as the center point determination.

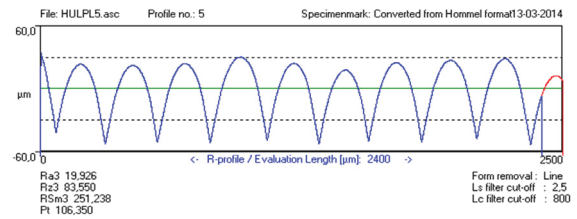


FIGURE 6. Roughness measurement of inside of printed hole.

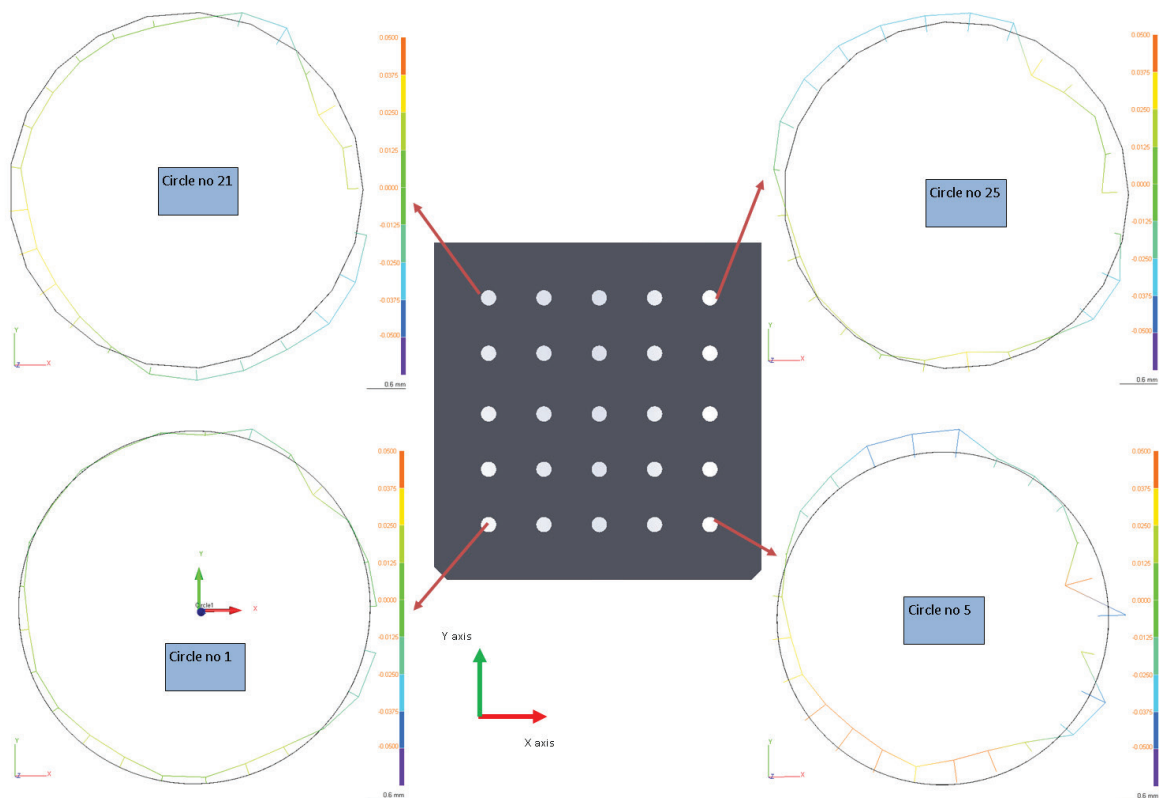


FIGURE 5. Roundness plots of selected holes. Roundness based on 25 measurement points.

Based on the above analysis an uncertainty estimation of length measurements was performed. The measurand was the length between center coordinates of holes. The CMM was calibrated using a high precision hole plate as described in [3,4]. Repeatability of center coordinates on the printed hole plate was assessed to be of the order of 6-7 μm (1s level) and temperature influences of the same order of magnitude. In total, uncertainties of the order of $\pm 20 \mu\text{m}$ on length measurements between center coordinates was estimated.

CORRECTION OF 3D PRINTER

The approach enables the determination of correction factors for scale errors both in X- and Y-directions based on the results presented in Figure 3. For the current paper three hole plates were printed, and the corresponding correction factors determined (Table 1).

TABLE 1. Correction factors for X- and Y-directions determined from 3 different printed hole plates.

	Correction factor	
	X	Y
Plate I	1,0017	1,0013
Plate II	1,0013	1,0008
Plate III	1,0014	1,0007
Average	1,0015	1,0009
Standard deviation	0,0002	0,0003

The correct application of these corrections factors would be to correct the FDM machine in its control software. As expected this turned out to be impossible due to a closed software. Recommendations from the machine vendor on different zero-setting procedures for the machines were followed, but without any visible results (Figure 6).

CONCLUSION AND OUTLOOK

The method described in this paper has been applied FDM based 3D printers. The hole plate enables correction of scaling errors, if the software of the machine allows such a correction. The total error encountered includes both axes errors and errors related to the process itself (in this case extrusion). The hole plate reflects a combination of these errors. In the future a separation of errors will be attempted.

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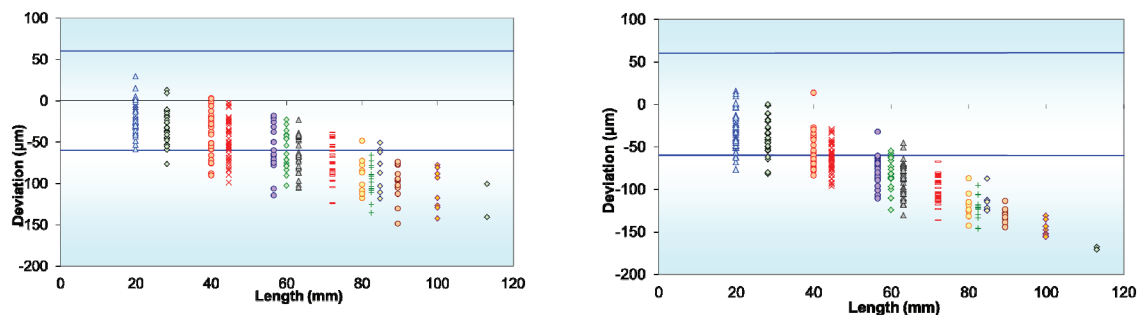


FIGURE 6. Example of length deviation plots for all lengths of hole plate. Left: Plate printed October 2013. Right: Plate printed January 2014. Full lines at $\pm 60 \mu\text{m}$ indicate rough specification of machine producer.

Abstract

Additive Manufacturing continues to gain momentum as the next industrial revolution. While these layering technologies have demonstrated significant time and cost savings for prototype efforts, and enabled new designs with performance benefits, additive manufacturing has not been affiliated with 'precision' applications.

In order to understand additive manufacturing's capabilities or short comings with regard to precision applications, it is important to understand the mechanics of the process. GE Aviation's Additive Development Center [ADC] is in a unique position to comment on additive metal processes and their dimensional capabilities. The former Morris Technologies has been producing Direct Metal Laser Melted parts since 2005 for a wide variety of industries. The retooled ADC now specializes in aerospace applications including GE's first production application: the LEAP fuel nozzle.

This paper and presentation will take a deep dive into the hardware and mechanics of the modern-day DMLM machine from three of the largest equipment manufacturers. We will also look at typical post processes including the heat treats that are commonly applied to DMLM metal parts. Along the way, we'll mention several surface finish technologies that have been investigated including one that is known as MMP [micro-machining process] which has been used to controllably remove microns of material.

Finally, the research will reveal one or two examples of techniques that have used to achieve tight tolerances at the ADC. These methodologies were employed to manufacture direct parts, where tolerances are not as tight as the conventional tools that would be used to produce such parts.

Readers and attendees should walk away with a better understanding of Additive Manufacturing, specifically direct metal parts, and the tolerances obtainable today. It is believed that this background information can help engineers and tool makers make better decisions about when to pursue Additive Manufacturing in their industry.

Steve Rengers

On-line Quality Measurements in laser powder bed fusion

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INTRODUCTION

Laser powder bed fusion (LPBF) is a layerwise production technique enabling the production of complex metallic parts. This process deposits thin metal powder layers on top of each other. Each layer is scanned selectively before the deposition of the next layer with a laser source by a predefined path, resulting in local melting of the powder. By repeating this layer by layer, a complex three dimensional model is produced. A schematic overview of the process is illustrated in Figure 1.

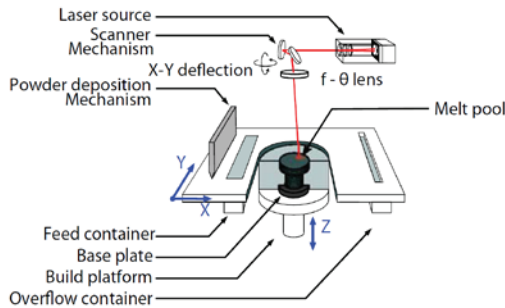


Figure 1. Schematic overview of a laser powder bed fusion process

Due to the high interest of the industry, the LPBF process has evolved drastically during these last years. Hardware improvements to increase the production speed and part size are being implemented by almost each machine vendor by building bigger machines with more powerful lasers. However for a large breakthrough of LPBF in high quality demanding sectors such as the aerospace industry, an important issue to be addressed is the validation of the quality. Currently the most used techniques to validate the quality are destructive testing, (which is very expensive since most products are unique or small series) and X-ray Computed Tomography (CT). This last non-destructive measurement technique is ideal for measuring the inside of

complex parts, however due to the high attenuation coefficient of metals the size of LPBF products that can be analyzed is limited and very time consuming and expensive [1].

To avoid these expensive quality control systems, an online monitoring system was developed at KU Leuven which will be discussed in this paper. Other monitoring systems with active illumination or with real temperature information are being developed by Lott et al. and Doubenskaia et al. [2-3].

EXPERIMENTAL SET-UP

All tests and developments of this monitoring system are performed at KU Leuven on an in-house developed Laser Melting machine (LM-Q). This machine is equipped with a 300W fibre laser ($\lambda=1064\text{nm}$) with a spot size of $80\mu\text{m}$ on the building plate and is controlled by an in-house developed real-time control system. This in-house developed machine is equipped with a coaxial monitoring system consisting of two modules [4].

The first important component of the setup is the optical system which is illustrated in Figure 2. In this figure two main light streams are visualized, the laser and melt pool radiation.

The laser source (4) sends out the laser radiation towards the galvano scanner (2) by reflecting on a semipermeable mirror (3). This semipermeable mirror reflects all light in a small bandwidth around the wavelength of the laser beam (1064nm) and transmits all other wavelengths. This scanner will then focus the beam with an f-theta lens onto the building plate (1) and selectively scans the surface.

While scanning the surface this laser beam melts powder particles and creates a melt pool which emits light towards the scanner in the opposite direction of the laser beam. This light passes through the semipermeable mirror and is

split into two light beams by a beam splitter (6) for two sensors. Before and after the split the light is filtered by optical filters (5,7,9) to avoid disturbances due to the visible light. This filtering of the light causes that the light reaching the sensors consists of light of a limited amount of wavelengths ($\lambda=780\text{--}950\text{nm}$), excluding directly reflected laser light of 1064nm .

These split beams are conducted towards two sensors: a high-speed near-infrared (NIR) thermal CMOS camera and a photodiode.

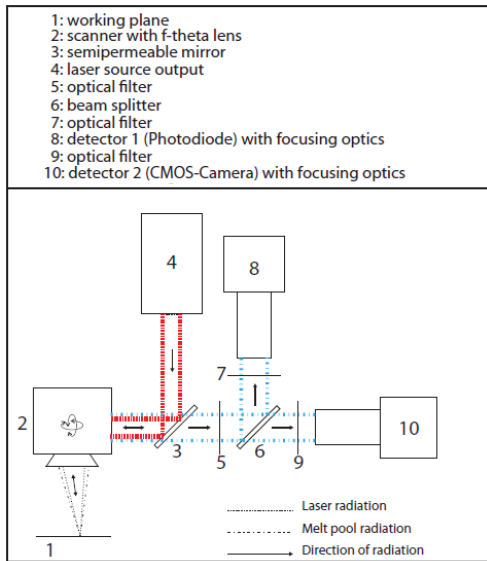


Figure 2. Schematic overview of the monitoring setup

The second developed part of the monitoring system is the data processing unit. This unit is necessary to achieve an accurate measurement of the melt pool at a high sample rate. This data processing unit is not necessary for sampling simple photodiode values but is of great essence to sample the camera. This unit is used to calculate all the necessary melt pool data out of the images of the camera at high sample rates.

The image processing is implemented on field programmable gate arrays (FPGA's). By limiting the region of interest of the camera image and implementing the image processing in hardware (on FPGA) a real-time measurement sample rates of at least 10 kHz can be achieved.

These sample rates are necessary since the speed for scanning the scan vectors (tool path) is often above 1000 mm/s. This would mean that for a sample rate of 10 kHz, every $100\mu\text{m}$ a sample is taken. Considering that the melt pool is expected to have a diameter around $150\mu\text{m}$, this should be sufficient.

The sensor values that are currently being sampled and calculated are:

- Melt pool intensity (photodiode signal)
- Melt pool area (camera images)

Other parameters such as melt pool length or width can be added in future [5].

The complete control of the LPBF machine (machine actuators, sensors and monitoring system) is implemented on a real-time PXI unit of National Instruments. This is done to have possibilities for future implementation of high speed real-time feedback control.

RESULTS AND DISCUSSION

The high sampling speed results in a lot of data which is difficult to interpret. Figure 3 is an illustration of the melt pool area versus time. This signal is very difficult to interpret.

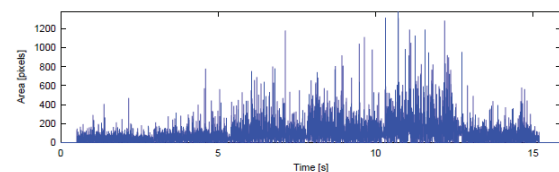


Figure 3. Signals captured during scanning of 6 cubic blocks in the titanium alloy Ti13Zr13Nb.

To get useful information out of these data, three scenarios could be applied.

The first one is averaging the signals over time. For example an average of the melt pool size for each layer. This will give only a very rough indication of the process and will only show big deviations in the process. An example of a deviation is the increase of the melt pool throughout the layers due to the heat accumulation in the part and base plate during the build job as a result of previous layers (Table 1).

Table 1. Table illustrating the average of the melt pool area (in pixels) of different layers throughout a build of Nickel Titanium cubes.

Layer number	Average melt pool area (pixels)
6	844
56	890
90	894
120	902
200	920

301	933
370	938

Since the deviations on the averages are very global, the signals could also be investigated with a slower thermography camera of the complete building envelope [6].

Rather than averaging all logged data (which eliminates a lot of information), one can also perform a detailed analysis of successive images. An illustration of such detailed analyses of 4 scan vectors can be seen in Figure 4. This image illustrates clearly that there is a peak in the melt pool size for every starting vector. This big variation in melt pool size results in porosities at the start of a vector (Figure 5).

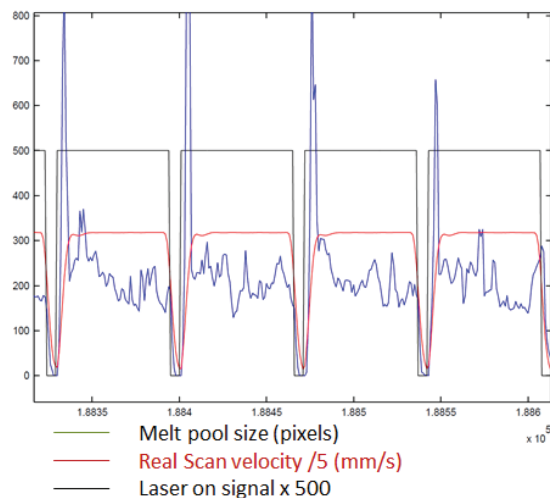


Figure 4. Melt pool size, Scan velocity and Laser on/off signal of 4 succeeding scan vectors during a build of cubic parts (in Ti6Al4V).

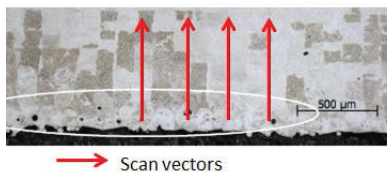


Figure 5. Microscopic image of a top view of a part build up by LPBF (Ti6Al4V).

This method seems to be efficient but due to the big noise on the signal (resulting from sparks in the process) and the big amount of data, this method is rather difficult to automate and therefore difficult to apply on a complete build job.

Resulting from this, a third method for interpreting the data was developed in

cooperation with Concept Laser gmbh. This method is more illustrative and is called the 'Mapping approach method'.

This method 'maps' the melt pool data in space. It basically does that for each layer by mapping the data on the X-Y plane. To apply this method the (x,y) positions of the laser beam on the powder bed should be logged simultaneously with the melt pool data. If this data is available a map can be generated by plotting the melt pool sensor values (e.g. area of the melt pool) on the corresponding simultaneous measured position in a X-Y graph, with the intensity at that point proportional to the magnitude of the melt pool signal (data). By this way 'maps' can be constructed showing at each location the magnitude of the melt pool which occurred at the corresponding location on the build platform. An illustration of the mapping of the data of Figure 3 is illustrated in Figure 6. This mapped figure is a complete different visualization method and is much easier to interpret by persons. Mapping all successive layers of a build job creates a stack of images similar to a CT image stack. Such an image stack can be very useful to analyze a complete part in an automated method.

These mappings give a detailed overview of a complete melting process of a layer in a small amount of data. However to use these maps for quality control, further research should be conducted to define correlations between mappings of dedicated melt pool characteristics (e.g. melt pool area) with quality properties (e.g. porosities). Some examples are illustrated below.



Figure 6. Mapping of the melt pool area signal using the signals presented in Figure 3.

Figure 7 illustrates the correlation between surface roughness and the mappings. At the left side a mapping of the melt pool area is illustrated while at the right side a measurement of the top surface is shown (scale of surface roughness: black = $-500\mu\text{m}$ and white = $+500\mu\text{m}$). Some correlations are clearly visible; others are very disputable. These maps show that there is a relation between the roughness of a surface and the melt pool size. Therefore the measurement of the melt pool area, can give an estimation of the roughness of the layer during processing.

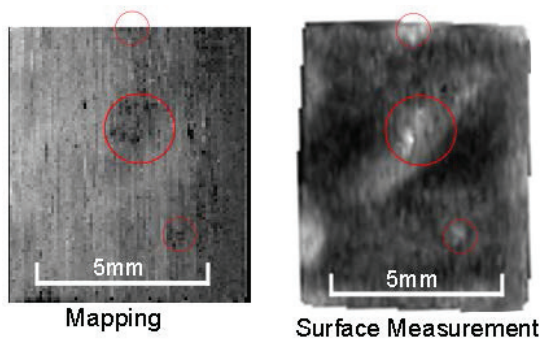


Figure 7. A mapping and a surface measurement of a layer.

Figure 8 shows the correlation between CT and maps generated from the logged data. Some correlation is found at locations where the CT image reveals pores, but there are however much more similar signals in the mapping that did not result in pores. Therefore a statistical strategy should be developed to improve the detection of pores based on the mappings.

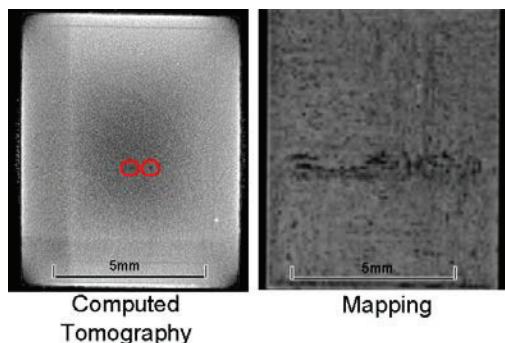


Figure 8. A slice of a Computed Tomography scan and a mapping of the same layer.

CONCLUSION

On-line quality control for the LPBF process is of great importance. The development of a system that can estimate the quality of the part on-line without the need for expensive destructive and

non-destructive testing, would be a major breakthrough for the process.

However to reach this level of quality control a lot of developments should be made. Monitoring the melt pool at high speeds is crucial to have an accurate and correct view of the complete part. The implementation of such a high speed monitoring system is implemented on the in-house developed LPBF machine at KU Leuven. Another step made towards the quality estimation is the method to visualize the big amount of data in an understandable figure. This is done by plotting the melt pool characteristics on their corresponding x,y position.

The correlation between these maps and the quality is however one big step that still needs to be made.

FUTURE WORK

In the near future more detailed investigation will be conducted to find the correlation between the already defined melt pool characteristics and quality factors. Also extra characteristics such as the melt length, width and their ratio will be examined.

Besides this monitoring, also plans are made to implement the first feedback control on the machine in order to control the average melt pool variations throughout the layers as was illustrated before.

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A HYBRID MANUFACTURING PROCESS FOR PRECISION METAL PARTS

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ABSTRACT

This paper presents the research and development of a hybrid manufacturing process to produce fully dense metal parts with CNC level precision. High performance metals, such as titanium alloys, nickel superalloys, tool steel, stainless steels, etc., can benefit from this process. Coupling the additive and the subtractive processes into a single workstation, the hybrid process, can produce metal parts with accuracy. The surface quality of the final product is similar to the industrial milling capability. It will certainly impact the future rapid manufacturing industry. To achieve such a system, issues, including the modeling of the metal deposition process and the automated process planning of the hybrid manufacturing process, are summarized.

INTRODUCTION

The Directed Energy Deposition (DED) process referred here is a metal additive manufacturing process in which metal is added to the part or product, layer by layer, to rapidly manufacture or form the part or product to a predetermined shape. It is a technique that can produce fully dense functional metal parts or tools directly from a CAD system and eliminate the need for intermediate steps. An example of DED process discussed in this paper is shown in Figure 1.



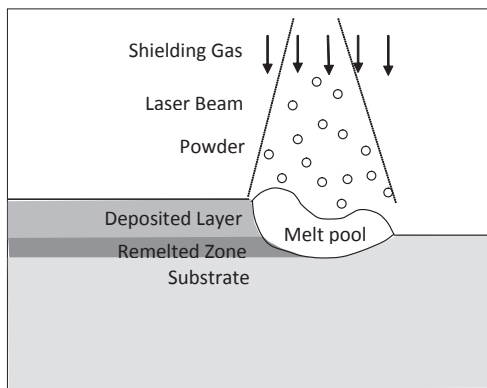
Figure 1. A blown powder metal deposition process is depositing a steel part.

A DED process is especially beneficial for high performance metals, such as fully dense titanium alloys, Inconel, and tool steel, which are difficult for traditional CNC machines or rapid prototyping (RP) machines to fabricate. For example, titanium and its alloys have proven to be technically superior and cost-effective materials for a wide variety of aerospace, industrial, marine, medical, and commercial applications. Parts or products cast and/or machined from these high performance metals are very expensive, partly due to the processing difficulties and complexities during machining and casting. DED processes however have been found to be very cost effective because they can produce near-net shape parts from these high performance metals with little or no machining. However, as DED processes cannot build support materials, multi-axis capability is critical in metal deposition technologies. The hybrid manufacturing process here combines laser deposition and machining processes to develop a rapid manufacturing process to build functional metal parts. This paper summarizes the research and development of such a hybrid process, including modeling and understanding of the direct laser deposition process for distortion, and automated process planning of the hybrid process.

DEPOSITION PROCESS MODELING

The basis of DED process is a sound microstructure which is dominated by the created melt pool during deposition. Melt pool formed during laser deposition is a critical factor and melt pool geometry is a crucial factor in determining deposition quality. To optimize process parameters, a deep understanding of the underlying mechanisms is beneficial. A mathematical model, as shown in Figure 2, was developed to simulate the coaxial laser cladding process with powder injection, which includes laser-substrate, laser-powder and powder-substrate interactions¹. The model considers

most of the associated phenomena, such as melting, solidification, evaporation, evolution of the free surface and powder injection. The fluid flow in the melt pool, which is mainly driven by Marangoni shear stress as well as particle impinging, together with the energy balances at the liquid-vapor and the solid-liquid interfaces are investigated. Powder heating and laser power attenuation due to the powder cloud are incorporated into the model in the calculation of the temperature distribution. The influences of the powder injection on the melt pool shape, penetration, and flow pattern are predicted by comparison between cases with powder injection and without powder injection. Dynamic behavior of the melt pool and the formation of the clad are simulated. The effects of the process parameters on the melt pool dimension and peak temperature are further investigated based on the validated model.



DISTORTION ANALYSIS

Highly localized heating and cooling during DMD process produces nonuniform thermal expansion and contraction, resulting in

Figure 2. Schematic diagram of the calculation domain for laser deposition process.

complicated distribution of residual stresses in the heat affect zone and unexpected distortion in the whole structures. The residual stresses may promote fracture and fatigue and induce unpredictable buckling during the service of deposited parts and the distortion is often detrimental to the dimensional accuracies of structures. Therefore, it is vital to predict the behavior of materials after DMD process and optimize the design/manufacturing parameters to control the residual stresses and distortion.

During DED process, the substrate will continuously experience expansion and

shrinkage and finally keep a deformed shape. Deformation in y direction, shown in Figure 3, is the main deformation under consideration and is observed by both experiments and simulations shown in Figure 4.



Figure 3: Deformation of substrate in y direction

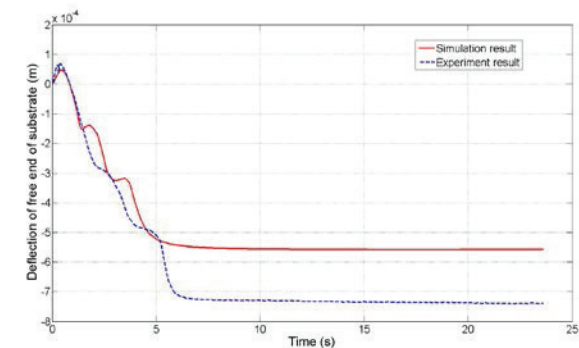


Figure 4: Simulation and experiment results of deflection of substrate.

The distortion analysis tool allows the planning of an effective hybrid manufacturing process so that the distortion effect could be minimized through the machining process.

HYBRID MANUFACTURING SYSTEM

In order to expand the applications of DED processes, multi-axis capability is needed. A multi-axis rapid manufacturing system can be hardware-wise configured by adding extra degrees of mobility to a deposition system or by mounting a laser deposition device on a multi-axis robot. The configuration could also be a hybrid system in which a laser deposition system is mounted on a multi-axis CNC machine. With the addition of extra rotations, the support structures may not be necessary for the deposition process in order to build a complicated shape. Due to the nature of the deposition process, it is driven by a so-called "slicing" procedure, which uses a set of parallel planes to cut the object to obtain a series of slicing layers. So far, the slicing software on the market is only able to handle 2.5D slicing in which the building/slicing direction is kept unchanged and it lacks the capability of

changing directions to fully explore the capability of multiple degrees of freedom.

This process uses laser deposition for material deposition and CNC milling for material removal. As shown in Figure 5, it includes two major systems: a laser deposition system and a CNC milling machine system.

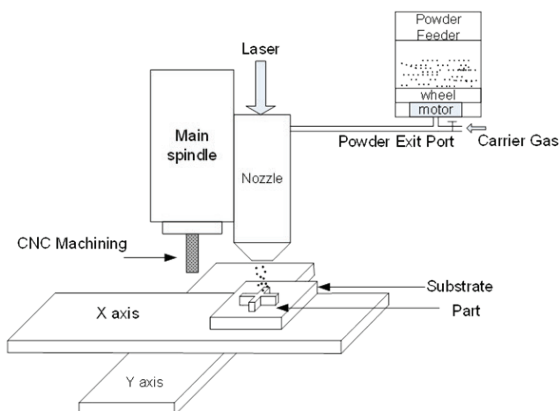


Figure 5. A hybrid manufacturing system: laser deposition for material deposition and CNC milling for material removal.

The laser deposition system and CNC milling machine work in shifts in a five-axis motion mode. The laser deposition system consists of a laser and a powder feeder. In a conventional 2.5-D laser deposition process to create three-dimensional parts, overhang and top surfaces of hollow parts must be supported. Often support materials for functional metal parts are not feasible. Moreover, it increases the build time of the part and necessitates a time-consuming post-processing. Additionally use of support increases the build time of the part and necessitates a time-consuming post-processing. With a five-axis deposition process integrated with five-axis machining, these obstacles can be removed.

HYBRID PROCESS PLANNING

The major issue to make an effective hybrid process is the automation of the system. Process planning, simulation, and tool path generation of a hybrid manufacturing process allow the designer to visualize and perform the part fabrication from the desktop. The Laser Aided Manufacturing Process Planning system uses B-Rep models as input and generates a description that specifies contents and sequences of operations. The objective of the process planning is to integrate the five-axis

motion and deposition-machining hybrid processes. The results consist of the subpart information and the build/machining sequence⁴. Basic planning steps involve determining the base face, extracting the skeleton, decomposing a part into subparts, determining build sequence and direction for subparts, checking the feasibility of the build sequence and direction for the machining process, and optimization of the deposition and machining²⁻⁴.

1) Skeleton Computation

An algorithm for computing the skeleton of the 3-D polyhedron is needed. The algorithm is based on a classification scheme for points on the skeleton computation in which the continuous representation of the medial axis is generated with associated radius functions. Because it is used as a geometric abstraction, the skeleton is trimmed from the facets that touch the boundary of the object along every boundary edge for which the interior wedge angle is less than $\frac{\pi}{2}$ rad. □

2) Part Orientation

The determination of the base face from which the building process of the part starts is very important. The base face functions as the fixture in the machining process. Therefore, when in the machining process, it must provide resistance against the cutting force. The maximal resistance force depends on the area of the base face.

3) Part Decomposition and Building Direction

The objective of part decomposition is to divide the part into a set of subparts, which can be deposited and machined. The topology of the part can be obtained from the skeleton. Each branch of the skeleton corresponds to a subpart. One of the partitions that is performed is along a non-planar surface. Therefore, close to the partition area, 3-D layers are needed to build the connection between two subparts. The build direction of a subpart may not be constant. It changes when the part is built layer by layer so that for two adjacent layers, the later layer can be deposited based on the early layer without any support structures. To achieve the non-support build, the build directions need to be along the skeleton.

4) Building Sequence

The results of decomposition are recorded in an adjacency graph where nodes represent subparts, and edges represent the adjacency relationship between connected nodes. After considering part building order, a directed graph that represents the precedence relationship among subparts can be constructed. From the

precedence graph, one can identify in what order the subparts can be built. With the precedence graph, a set of alternative building plans can be generated. Each plan represents a possible building sequence on the decomposed geometry and can be chosen optimally depending upon machine availability or other criteria such as minimum building time.

5) Machinability Check

The main purpose of the machinability check is to choose an optimal building sequence from the sequence set. Local and global collision checks are operated first to choose acceptable sequences since the building direction is different in each sequence. If any kind of collision happens or an undercut plane appears, the corresponding sequence will be discarded. For the rest of the building sequences in the set, the buildability check and machining time computation is performed to find an optimal building sequence.

RESULTS

The bearing seat example as shown in Figure 6 (a) and its deposition result are shown here. Figure 6 (b) shows the planned tool path for both deposition and machining, Figure 6 (c) shows the part in H13 tool steel being deposited, and Figure 6 (d) shows the part after machining.

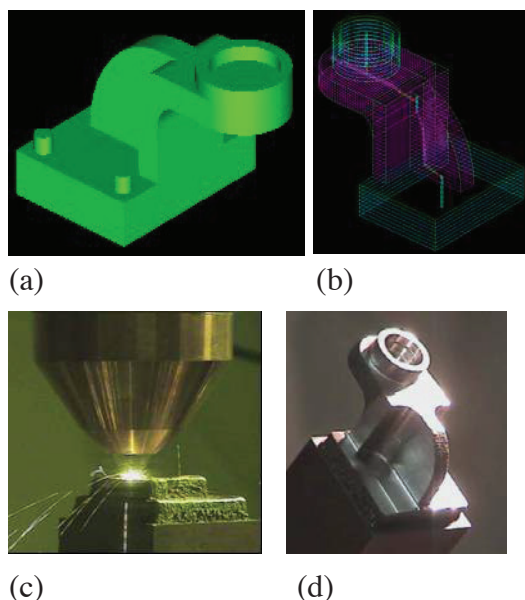


Figure 6. Hybrid manufacturing of an H13 tool steel bearing seat part: (a) CAD model (b) Automated generated tool path for deposition and machining; (c) Laser deposition; (d) After machining.

CONCLUSION

Making precision metal parts is a critical additive manufacturing technology as it can directly produce finished products or parts for high performance applications. The current limitations of additive processes include surface finish, repeatability, and material properties. The research and applications of a hybrid metal manufacturing system are summarized in this paper. The issues include understanding the DED process, and the automated process planning. The modeling and simulation of material-laser interaction help design and set the process parameters for metal deposition. The overall goal for process planning is not only to find a solution to build a part but also to look for an answer to produce it in the least amount of time; therefore, the least amount of switching between the machining process and deposition process, the better since each switch requires retreating and relocating the deposition nozzle as well as the machining tool, which may cost extra time. With integration of multi-axis deposition and machining processes on the same work station, a hybrid system is able to produce complicated geometry, especially the overhang structure with less or no support structures. Based on different geometry shapes, the five-axis system can save close to 100% of support materials. The surface quality of the final product is similar to the industrial milling capability. As there is a big demand in precision metal additive manufacturing applications, a more sophisticated process planner and general purpose for hybrid manufacturing systems is needed.

ACKNOWLEDGMENTS

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Improving Dimensional Accuracy and Surface Finish on Freeform Components Using Commercially-Available Machine Tools

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Introduction

Ultra-precision machining is a finishing process. Almost all components require some sort of pre-machining process that requires large amounts of material removal to get to net shape prior to moving to the ultra-precision process. Furthermore, ultra-precision machining is generally a slow material removal process, especially in the case of raster milling freeform shapes. For these reasons, it is very desirable to have the base material as close to net shape as possible. This is now readily achieved with the advent of Additive Manufacturing. AM has the added advantage that it can create shapes that would not otherwise be possible.

Ultra-Precision Machine Tools

Key components of ultra-precision machine tools include extremely stiff and accurate rotary tables and spindles, and very straight and stiff linear axes that can travel at high speeds and accelerations with high servo bandwidths and increments of motion under 1 nm. A typical slide configuration is shown in Figure 1. These slides are mounted to a stable granite base, and they are guided by externally pressurized oil bearings. Using glass scales to sense position, a high speed digital controller drives the slides with linear motors. By these means, very repeatable straightnesses of motion under 150 nm over 200 mm of travel are achievable.

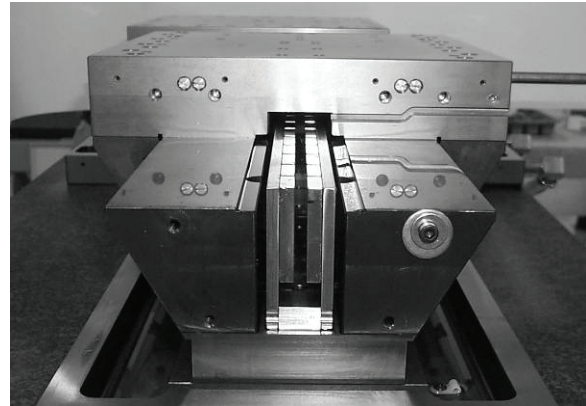


FIGURE 1. End view of an ultra-precision slide.

One of the most critical components of any machine tool is the spindle, whether it is the tooling spindle or the work piece spindle. Externally pressurized air bearing spindles are commonly used on ultra-precision machine tools. Error motions under 15 nm are possible up to speeds of 10,000 rpm and 30 nm up to 80,000 rpm. Water cooling is a must for these spindles to minimize thermal growth, which is the largest source of machining errors.

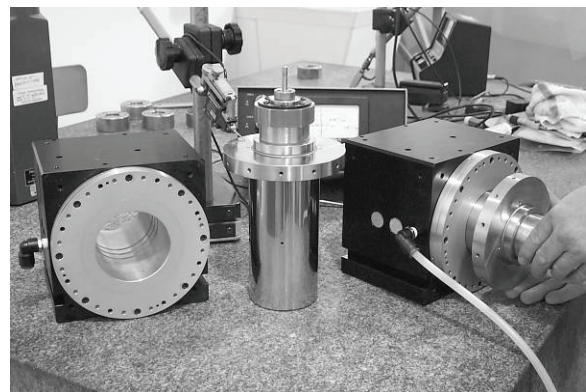


FIGURE 2. Components of an ultra-precision, air bearing spindle.

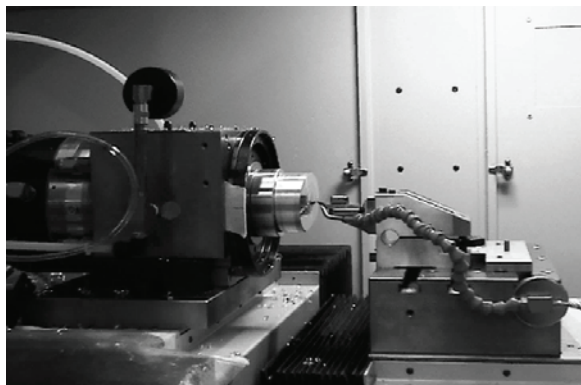


FIGURE 3. An ultra-precision lathe.

Early ultra-precision machine tools were limited to only turning operations with the coordination of two, slowly moving linear axes. Today's machines and controllers can precisely coordinate four, or more, rapidly moving axes, including short stroke, Fast Tool Servo axes moving at frequencies in excess of 1000 Hz. Ultra-precision machine tools are now capable of creating freeform surfaces with 100 nm form errors and 2 nm Ra surface finishes. By incorporating a high resolution encoder in the air bearing spindle, its position can be controlled to within 0.0001 degrees while spinning in excess of 1000 rpm. This capability enables the rapid generation of freeform surfaces.

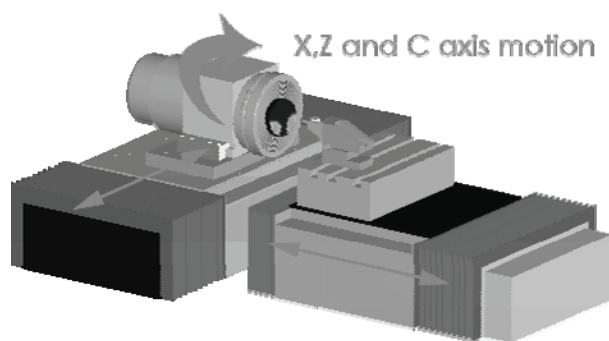


FIGURE 4. A lathe configuration for generating freeform surfaces with three coordinated axes.

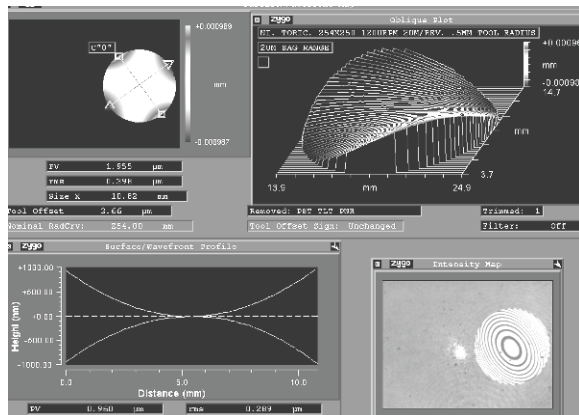


FIGURE 5. Form measurement of a toric surface cut by XZC motion at 1200 rpm. The form error is under 100 nm PV.

Because of limitations on tool clearance angles, the slopes of a freeform surface are limited to 35 degrees for XZC turning. For steeper surfaces, the tool must rotate, as is done with milling or flycutting. A milling spindle can be added to an XZC lathe to combine the benefits of turning some features in the same set up.

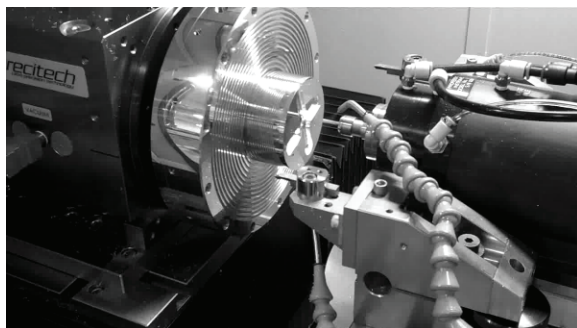


FIGURE 6. Milling and turning on an XZC lathe.

Ultra-precision machine tools also come in a more traditional milling machine configuration with three linear axes. Figure 7 shows an XYZ milling machine with a vertically mounted milling spindle. This machine has slides with 150, 300 and 350 mm of travel and an optional

rotary C axis where the work piece can mount. In this configuration, a variety of milling and grinding spindles can be used, including ones with speeds over 125,000 rpm. Figures 8 and 9 show a horizontally mounted milling/flycutting spindle on the vertical axis. A very wide range of freeform surfaces can be created with a variety of rotating tools that are rastered over the freeform surface. The surface slope constraints are greatly relaxed with this machining method, but it comes at the expense of prolonged cutting times. Because the horizontal spindle can also operate in positioning mode, this machine can operate as a five axis machine with a B axis mounted to the Z axis. As shown, this spindle is limited to 10,000 rpm, but this configuration has an advantage in that it can revert to an XZBC turning machine, as shown in Figure 10. If higher speed, five axis milling is required, a milling spindle can be mounted to B with the work piece on the C axis as shown in Figure 11.

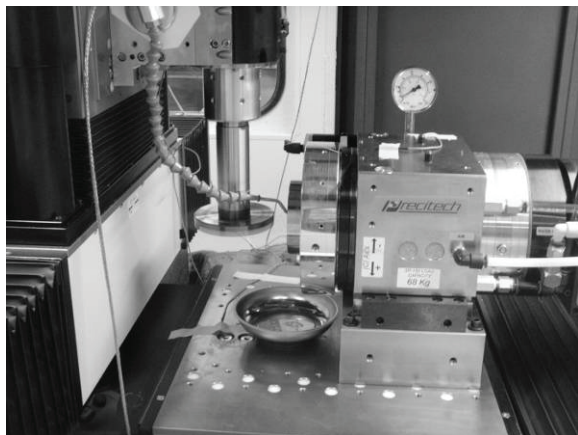


FIGURE 7. *XYZ Freeform flycutting machine with a rotary axis.*

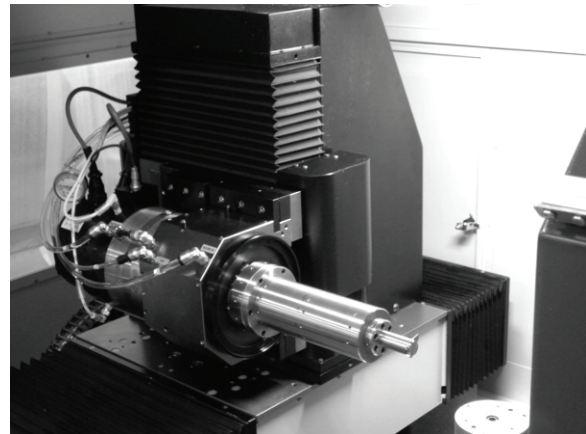


FIGURE 8. *XYZ flycutting with a horizontal spindle.*



FIGURE 9. *Raster flycut lens mold using XZYB motion.*

Tooling Considerations

Diamond has many special properties that enable it to be an ideal tool for cutting many materials. While diamond tools work particularly well on polymers, copper and aluminum alloys and on nickel phosphorus plating, they work less well on ferrous materials. For difficult materials, CBN tools are substituted for diamond with some loss of finish and form. Single crystal diamond can be polished to an accurate, atomically sharp edge, and when this is combined with its high hardness, high conductivity and low coefficient of friction, a tool is created that cuts very

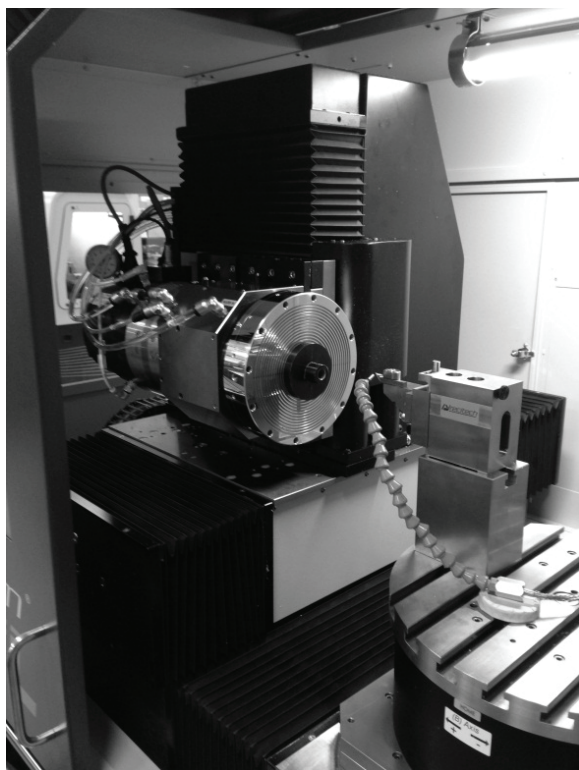


FIGURE 10. Turning configuration with a rotary B axis.

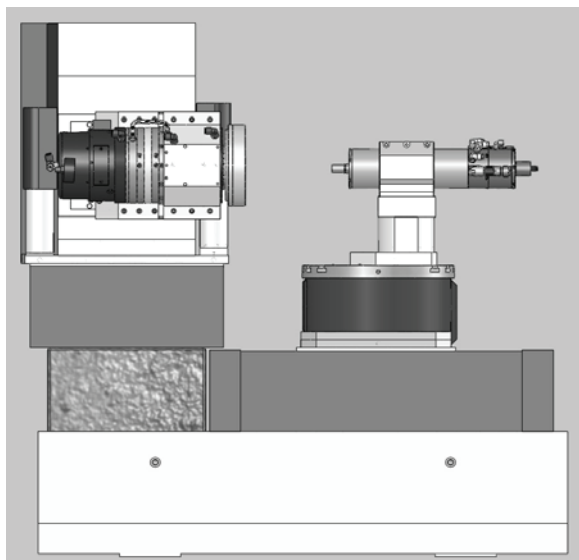


FIGURE 11. Five axis milling machine configuration.

cleanly with no built up edge and low surface damage. This capability is key when trying to machine optical quality surfaces. When this level of finish is not

required, cheaper poly-crystalline diamond, carbide or CBN tools can be substituted on an ultra-precision machine with little loss of form accuracy. In fact, when high surface finish is not required, the machining times and tool wear are much less, which usually results in improved accuracy, despite the higher cutting forces. It is a common misnomer that ultra-precision machine tools cannot take heavy cuts. In actuality, ultra-precision machine tools are much stiffer than traditional machine tools and their motors are sized to generate cutting forces in excess of 100 N. The AM community should take particular notice of nickel-phosphorus. This ultra-pure material can be plated onto many substrate materials in layers up to 2 mm thick. In its amorphous state, it is the hardest and most inert material that can be readily diamond turned. Rockwell C hardnesses of 52 are possible.

Conclusions

Ultra-precision machine tools have progressed significantly over the 50 years since the advent of diamond turning in the US. While these machines have mostly been applied to the fabrication of optics, they have growing utility outside of optics. Marrying this technology with AM opens even more applications. Because some of the aluminum and copper alloys used in AM are compatible with diamond tools, even some optical applications for AM are feasible. Two applications in particular come to mind, water cooled copper mirrors with intricate cooling passages for high power lasers and lightweight optical mounting structures.

Powder Bed Fusion Machine Performance Testing

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INTRODUCTION

Although additive manufacturing (AM) is often referred to as a “disruptive technology,” there are many ways an AM process is similar to conventional processing methods. Raw material is prepared for the processes: casting, forging, forming, powder creation, etc. Then the process is performed by a machine on the prepared material: turning, milling, grinding, electrical discharge machining (EDM), laser drilling, powder bed fusion, etc. Finally, the processed part is typically post-processed—heat treatment, deburring, polishing, etc.—to obtain desired material properties, surface condition, etc.

Independent of the processing path, there are four basic categories of quality for all processed parts: dimensions, form, surface finish, and material properties. One approach to understanding the contributions of the machine performance to the overall part quality is to begin with a list of independent error motions of the machine components. For a traditional machine tool, these are the well-known parametric and geometric errors of the axes, but AM machines require more thought and study.

GEOMETRIC ERRORS IN MACHINE TOOLS

The accuracy of the positioning of a conventional linear machine axis depends on the accuracy of the scale (or other position feedback device) together with two angular errors, each paired with an offset distance. The two angular error motions are typically called pitch and yaw. The lateral offsets are from the scale position to the point where the workpiece and cutting tool intersect in a plane perpendicular to the nominal motion. Straightness is the lateral deviation from the nominal axis direction, which is also dependent on the position of the functional point and two angular error motions. In this case, the angular errors are roll and either pitch or yaw. However, an offset of

the functional point perpendicular to the motion in the direction of the straightness deviation is typically assumed to not affect straightness.

Typical 3-axis machine tools generally consist of a combination of stacked linear axes. As such, with a known tool location and point of contact with the workpiece, the systematic portion of the errors can be predicted from the measured data of 21 well defined tests: 3 linear accuracy tests (1 for each axis), 6 straightness tests (2 for each axis in perpendicular directions to motion), 9 angular error motions (3 for each axis), and 3 squareness tests (YX, ZX, and ZY) [1]. Note that many of these tests can be performed simultaneously.

PBF MACHINES ARE MORE CHALLENGING

Laser-based powder bed fusion (PBF) additive manufacturing machines also follow the concepts of axes for motion and positioning [2], but the concept of the functional point and the method of actuating that point are different. In these processes, thermal energy from a laser beam selectively fuses regions of a powder bed. Figure 1 shows a two-dimensional (2D) schematic of the process. A computer model of the part's geometry is virtually sliced into discrete layers. The laser traces the geometry of an individual layer onto the top surface of a bed of powder material. After an individual layer is completed, the build platform (and therefore the entire powder bed) is lowered by the prescribed layer thickness, and a new layer of powder is swept over the powder bed, filling the resulting gap. The top surface of the powder bed is created by the recoating blade as it drags powder from the dispenser bin onto the powder bed. The laser then traces the geometry of the next layer to be built.

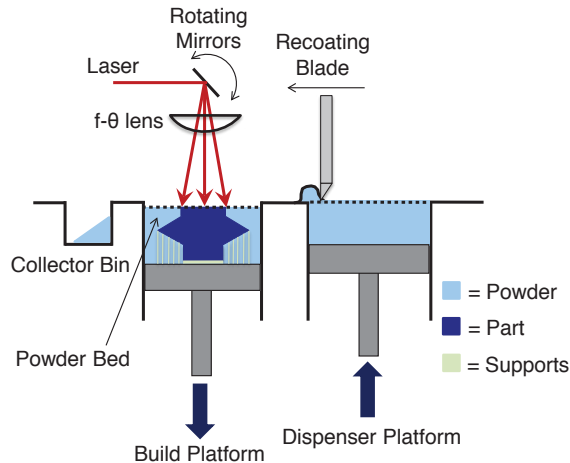


FIGURE 1. TWO-DIMENSIONAL SCHEMATIC OF A LASER-BASED POWDER BED FUSION ADDITIVE MANUFACTURING SYSTEM.

The functional point for PBF processes (i.e., the point where the part is being formed) is the point where the laser beam meets the top surface of the powder bed. Laser-based systems typically deflect the laser beam off two mirrors and through some optics (often an $f-\theta$ lens) to focus the beam on the top surface of the powder bed. The beam spot is moved by a galvanometer system that rotates the deflecting mirrors (see Figure 2).

The measurement of geometric errors and the ability to predict systematic errors is different in PBF machines than for machine tools. Accuracy

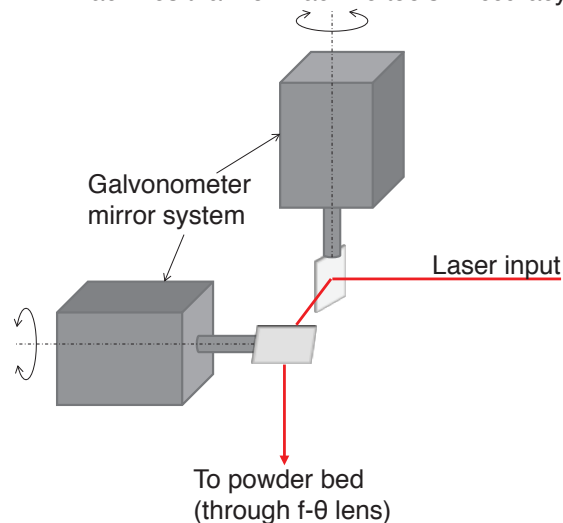


FIGURE 2. SCHEMATIC DEPICTING THE GALVANOMETER AND MIRROR SYSTEM USED TO MOVE AND POSITION THE LASER BEAM SPOT ON A TYPICAL POWDER BED FUSION MACHINE.

of positioning the beam spot or straightness of the path of the beam spot could theoretically be measured along a nominal axis direction of the machine. However, these accuracy and straightness measurements do not provide information to predict the accuracy or straightness along any other line, or, given two orthogonal lines of measurement, at any arbitrary point. The systematic errors in the position of the laser spot in the x - y plane arise from inaccuracies in the positioning of the galvanometer mirrors, the geometric quality of the optical system alignments, the quality of the mirrors, imperfections of the $f-\theta$ lens, and the profile of the laser beam.

A complete characterization of laser spot accuracy in the 2D plane of the top surface of the powder bed could theoretically be done with an accurate representation of the machine component geometry along with detailed mapping of optical surfaces and measurement of mirror axis rotational accuracy. However, in general, this approach is impractical, requiring possible disassembly/reassembly of the machine's optical system and specialized optical test equipment. An alternate approach is to test point positioning accuracy using a workpiece or testpiece that has a sufficiently dense grid covering the entire workzone. Since the grid cannot practically be infinitely dense and because such a grid is often used to create a lookup table or parametric error representation for real-time correction, a different pattern must be used to test the resulting performance of the machine in the x - y plane.

When a test grid is generated to establish the accuracy in x and y , there are many error components which are not easy to resolve: scale errors from galvanometers, uncertainty in the kinematic geometry, and optical aberrations. While it is not necessary to measure all error components independently, it is desirable to quantify the systematic and non-systematic portions of the X - Y error so that corrections can be applied for the systematic errors and the non-systematic portion of the error can be used to establish expected performance.

DESIRED MEASUREMENTS

The non-systematic error is mainly related to thermal effects and 6 degree-of-freedom relative motion of the optical system relative to the part x - y plane. This suggests a drift test of optics to the recoating blade may be appropriate, although the test setup is difficult to imagine compared to conventional metrology methods.

The build platform, moving in the machine's z-direction, most closely resembles a traditional machine tool axis, leading one to consider the standard axis performance tests. However, while the linear accuracy of positioning through the Z-axis range relates to dimensions of finished parts or features with dimensions in the z-direction, variation in positioning accuracy over shorter distances relates to variation in layer thickness. This could have important consequences in the process performance, causing balling or incomplete melting, which lead to porosity or line/area defects. For example, in a conventional linear accuracy test [3-5] a maximum error at any point of $10\text{ }\mu\text{m}$ yields a test result of $10\text{ }\mu\text{m}$ for the axis. The axis could fluctuate between $+5\text{ }\mu\text{m}$ and $-5\text{ }\mu\text{m}$ at very high spatial frequency and still the axis result would be $10\text{ }\mu\text{m}$. On a powder bed fusion machine, if the platform motion contained errors of $+5\text{ }\mu\text{m}$ and $-5\text{ }\mu\text{m}$ at a high spatial frequency, this could represent a 50% variation in layer thickness from the nominal programmed value, leading to possible defects throughout the entire thickness of the part. As such, both long range and short range measurement of the Z-axis is desired.

While it is true that the build platform moves the entire powder bed, the positioning of the build platform does not set the top surface of the powder bed; the movement of the recoating blade defines the top powder surface. In most machines, the recoating blade moves in the machine's x-direction. The error motions causing deviation in the top powder surface are the straightness in the z-direction along with the roll of the recoating blade. Note that non-flatness of the powder surface leads to inconsistencies in the layer thickness, as described in the previous paragraph, and small position deviations in the x-y plane as well, as illustrated in Figure 3.

MEASUREMENT METHODS

The high powers of the lasers used in PBF machines make measuring the positioning of the beam spot rather challenging. If the laser power could be sufficiently lowered, one could envision the beam spot being projected down onto a large position sensitive device (PSD, using photodiode surface resistance) that would measure the position of the focused beam relative to an established datum on the PSD. However, most PSD systems cannot handle more than a few milliwatts of laser power, let alone the tens or hundreds of watts from PBF lasers.

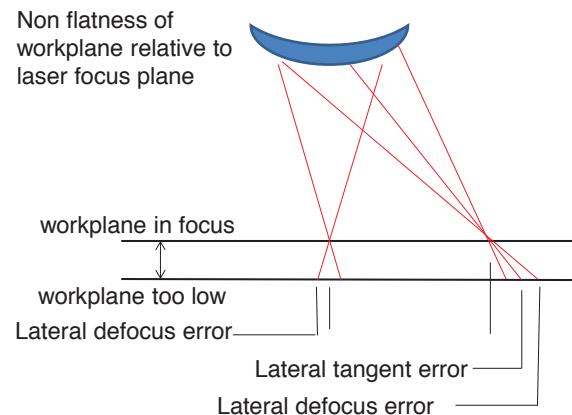
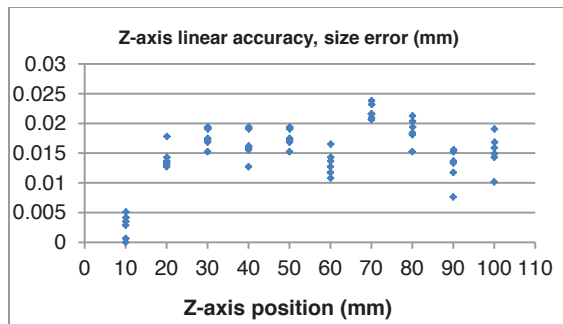


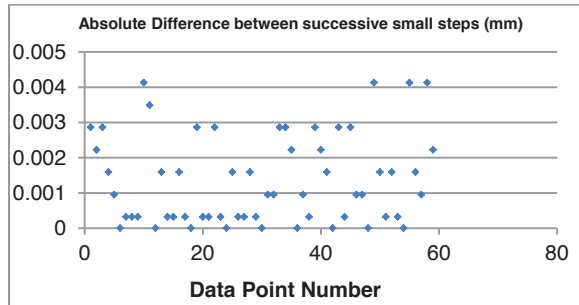
FIGURE 3. RAY DIAGRAM SHOWING SMALL LATERAL DEVIATIONS RESULTING FROM IMPROPER HEIGHT OF THE TOP POWDER SURFACE.

Absent a direct method of measurement, test artifacts can provide a viable measurement. The likely test artifact in this case would be a 2D planar artifact. A temporary building platform can be inserted into the machine and brought into the focal plane of the laser. The machine can then be programmed to burn only one layer of a test part with geometry suitable to test the performance of laser spot positioning. The temporary platform can be removed and evidence of the laser path can be inspected for geometry. The specific geometry and the method of measurement are still under development.

The measurement of positioning of the build platform can follow traditional approaches using either laser interferometer or gage blocks with dial indicators. The measurement should be conducted between the build platform and the recoating arm. Most PBF machines position only in one direction—when moving down, the build platform travels past its target position, stops, and then moves upward to the target position. As such, only uni-directional measurement is necessary. A series of a long movement (on the order of 10 mm) followed by several very short movements (on the order of $20\text{ }\mu\text{m}$ or a typical layer thickness) is likely most appropriate. The results should be split into long and short positioning accuracies. Figure 4 shows measurement data in this format.



a



b

FIGURE 4: RESULTS FROM POSITIONING ERROR TEST OF Z-AXIS. A: SIZE ERROR IS DIFFERENCE BETWEEN ACTUAL AND PROGRAMMED POSITION. B: LAYER ERROR IS ABSOLUTE DIFFERENCE BETWEEN ACTUAL AND PROGRAMMED POSITION FOR SUCCESSIVE NOMINAL MOVES OF 20 μm .

CONCLUSION

Unlike conventional machining where there is a near 1:1 correspondence of machine performance to the geometry of the workpiece, the accuracy of the machine components is only one of the contributors to the quality of a finished AM part. Rather, there is interaction with other process variations such as quality of the powder, stability of the laser electronics, etc. that affects all aspects of product quality related to dimensions, form, surface finish, and properties of the finished components. It is important to understand these relationships and the role of the mechanical accuracy.

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ⁱ Official contribution of the National Institute of Standards and Technology (NIST); not subject to copyright in the United States. The full descriptions of the procedures used in this paper require the identification of certain commercial products. The inclusion of such information should in no way be construed as indicating that such products are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software or suppliers for the purposes described.

SURFACE TEXTURE MEASUREMENT FOR ADDITIVE MANUFACTURE

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INTRODUCTION

The lack of clarity in how to measure the surface topography of additively manufactured (AM) parts, together with the unpredictability of the surface topography, are barriers to the adoption of AM processes by industry.

Correspondence with several AM machine manufacturers has revealed that they assess surface texture using tactile profiles taken across the lay of the component and primarily by assessing *Ra* and *Rz*. In published research to date, the surface texture is also generally reported as an *Ra* value, based on measurements across the lay.

There have been several attempts to model and hence predict AM surface texture [1], [2]. More recently, the influence of powder particles has been incorporated into a mathematical model [3]. However, a literature search failed to identify research that explores the appropriateness of *Ra* or other parameters, or the importance of lay when characterising AM surfaces.

The long-term aim of this work is to understand the effect and relative importance of the factors which influence AM surface texture, so as to give manufacturers sufficient information to adapt the component geometry and/or process to achieve the surface texture needed for the surface's function. In the short term, the aim is to understand the way AM surfaces should be measured in order to characterise them, and to recommend a measurement method to potential users of the AM process.

In this work, a preliminary investigation was carried out on two metal AM powder bed

processes, selective laser melting (SLM) and electron beam melting (EBM).

INVESTIGATED KEY PROCESS VARIABLES

The surface texture of AM metallic surfaces is affected by a number of factors, including:

- material;
- particle size and distribution [4];
- the effect of heat buildup [3], [5];
- the thickness of the printed layers;
- the angle of the surface relative to the horizontal plane of the build bed;
- the effect of any post processing/finishing; and
- the position of the component in the build chamber.

These factors were all considered when choosing a coupon design for the experiment. To minimise the number of key process variables (KPVs) being assessed, flat coupons were used, with a fixed layer thickness and a single material, titanium alloy (Ti6Al4V). Samples were manufactured at four angles relative to the horizontal plane of the build bed (see Figure 1) using both SLM and EBM. Coupons below 45° build angle had to be supported during the build, as shown in Figure 2.

The samples were imaged under a scanning electron microscope (see Figure 3). They were then measured on both the upskin and downskin¹ using a variety of optical and tactile

¹ The terms 'upskin' and 'downskin' are used to refer to the upward-facing and downward-facing surfaces respectively of the coupons as they were oriented on the build bed of the AM machine.

methods at MTC and NPL, both along and across the lay. Samples were also sectioned by Alstom and evaluated using their proprietary image analysis method to evaluate R_a using a simulated probe. Following grit blasting with alumide, the above measurements were repeated.

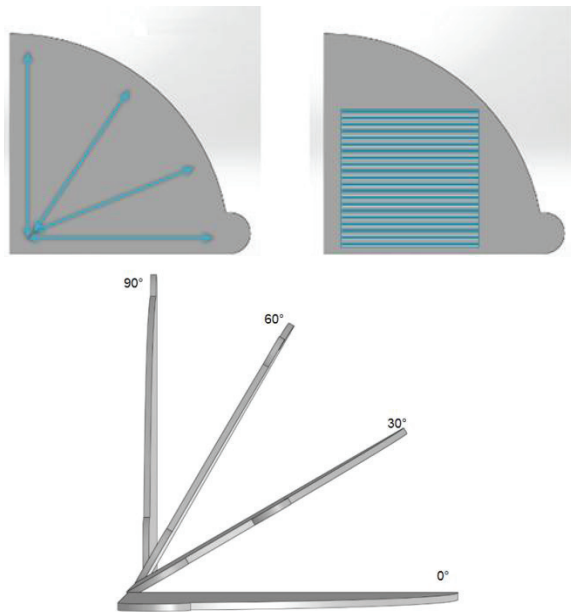


FIGURE 1. Geometry of samples and angle relative to horizontal build bed.

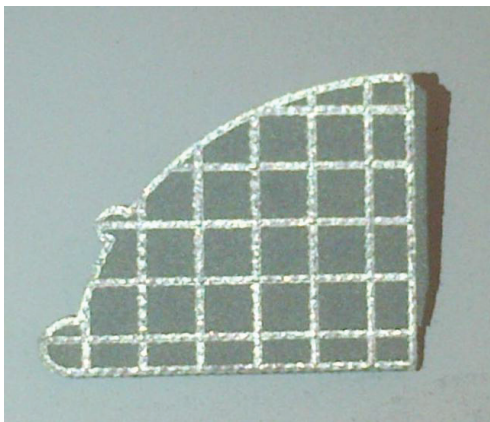


FIGURE 2 Underside view of the 30° EBM coupon showing the support 'wafers'.

The appropriateness of the ISO specification standards on tactile profile measurement [6] to AM parts was also investigated as was the practicality of tactile and optical measurement methods.

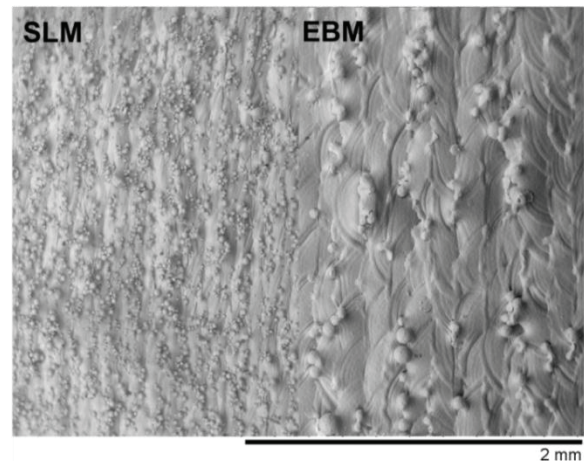


FIGURE 3. Image obtained under scanning electron microscope of samples printed by SLM and EBM at 30° to the build bed.

RESULTS

The measured value of the R_a parameter for each of the build angles was compared using profile, areal and image analysis methods. Figure 4 shows an example of tactile profile measurements conducted at MTC. The effect of build angle on R_a is evident.

The direction of the profile with respect to the lay, however, was found not to be a significant factor, being masked by the deviation in surface texture values over the area being measured.

Optical areal measurement of the coupons indicated that a 2.5 mm by 2.5 mm evaluation area is sufficient to capture the significant characteristics of the AM surfaces measured in this work. An example of such measurements is shown in Figure 5. The complexity of the sample (average gradient over a decade of the relative area, [7]) indicates that the spatial wavelength of interest is below 2.5 mm, which in Figure 5 corresponds to the region on the right hand side of the peak where the curve plateaus (approximately $3 \times 10^6 \mu\text{m}^2$ on the x-axis of Figure 5). Therefore, there is no need for an L-filter nesting index larger than 2.5 mm. The position of the peak is an indication of a major change in the relative area between two successive tile sizes. Note that at this level of R_a , ISO standards would recommend an evaluation length of 8 mm.

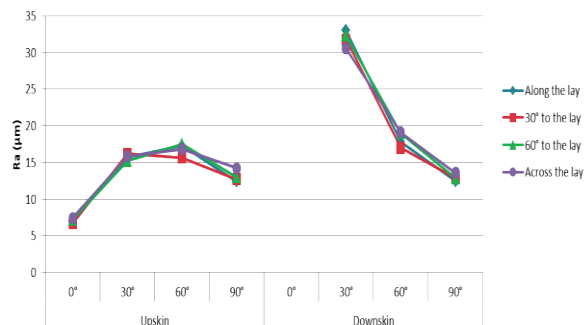


FIGURE 4. Tactile Measurement results on as-built SLM coupons showing R_a against build angle

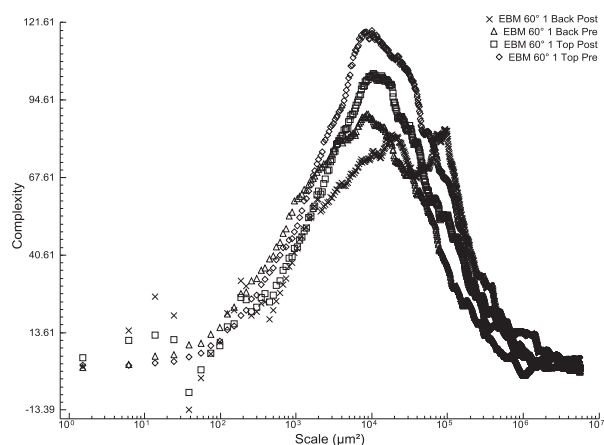


FIGURE 5. Area scale analysis results for EBM as-built coupon produced at 60°: upskin as-built (denoted by ◇), downskin as-built (denoted by △), upskin post-processed (denoted by □) and downskin post-processed (denoted by ×)

Without any functional specifications and with only a loose requirement for calculating S_a , the selection of relevant areal parameters was difficult. The S_{sk} parameters showed potential for differentiating between the upskin and downskin of the coupons and this applied to both the pre- and post-processed surfaces. At this stage, given the nature of the surface, it was found that there was no immediate areal parameter that can be applied for AM surfaces. Further recommendation of preferred measurement parameters would depend on the intended function of the surface, as is the case with surfaces manufactured conventionally.

The samples that were sectioned and measured by Alstom showed R_a values that were generally in alignment with the tactile profile measurement results. A secondary - but significant - result of the imaging analysis was that re-entrant features are evident on the coupon surfaces, an example of which is shown in Figure 6. These features do not affect the stylus or optical measurements.



FIGURE 6 As-built EBM section images of 60° upskin (Alstom)

There was initial uncertainty as to whether optical measurement methods are suitable for AM surfaces. The surfaces combine a reflective material together with an omnidirectional particulate surface characteristic, which could have been expected to cause problems with reflected light based measuring instruments. During the project, however, no optical artefacts or other limitations were observed which would preclude the use of optical measurement methods for such surfaces.

The SLM process requires that supports are used on downskins from approximately 45° build surface angle (depending on build material). For the project, an attempt was made to position the supports such that a tactile probe could measure in between the support witness marks however in practice this proved difficult and the downskins could not be measured. The same applied for the EBM coupons where support wafers were used. This highlights a problem in surface characterisation, namely that the downskin surfaces are sometimes not clean enough to be able to measure without significant post-processing.

CONCLUSIONS

The implications of being able to use a 2.5 mm by 2.5 mm evaluation area to characterise an AM surface (as opposed to an 8 mm by 8 mm area) are significant:

- smaller features can be used to characterise an AM surface,
- less time is required to take the measurement when using tactile methods.
- with optical methods, image stitching may be avoidable.
- there is less chance of damage to the stylus tip – that has been anecdotally observed with EMB surfaces - if a tactile method is used.

An additional important result is the lay not being statistically significant in terms of *Ra* values on the surfaces that were measured. This factor in itself makes AM surface characterisation easier, since there are many times when a feature does not align with the lay of the surface, making choosing a measurement location and direction difficult.

The re-entrant features identified using Alstom's imaging method highlight the need for further work into what produces re-entrant AM features and how to characterise them. These features would not be picked up using non-destructive optical or tactile methods, but would have a significant impact on the fatigue life, for example, of an AM component.

FURTHER WORK

The findings of this work need to be verified with other surface build angles and other materials

The equivalence of a 2.5 mm by 2.5 mm areal measurement window to tactile profile measurement trace lengths needs to be verified.

The extent of re-entrant features needs to be evaluated over the whole range of surface build angles from 0 to 360°.

A survey of potential end-users of AM to collate a set of intended surface functions is essential. The survey would help direct further research into detailed characterisation of AM surfaces.

ACKNOWLEDGEMENTS

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Thanks are due to Matthias Hoebel and Felix Roerig (Alstom) for sectioning the SLM and EBM samples and conducting image analysis on them.

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METROLOGY FOR ADDITIVE MANUFACTURING PARTS AND PROCESSES

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INTRODUCTION

Additive manufacturing (AM) comprises a range of deposition processes which include, but are not limited to, direct metal laser sintering (DMLS), electron beam melting, direct metal deposition, photo polymerization, stereolithography, and fused deposition modeling. While rapid prototyping techniques have been available for more than two decades [1, 2], AM has experienced phenomenal growth in recent years driven by new applications and processes associated with design, prototyping, limited quantity production, tooling and fixturing, and repair or modification of existing parts. The advantages of additive manufacturing include reduced setup costs, fast turnaround, and the ease of fabricating designs that lack symmetry, that include arbitrary freeform geometries, and/or that include complex internal geometries. While metrology tools exist that are useful for additive parts and processes, AM provides challenges which have not yet been addressed by industry or the research communities.

Any designer has in mind functional requirements, and through the design, satisfies these functional requirements. While design parameters include material properties and geometry, the current work is limited to how additive manufacturing technologies meet geometry requirements such as part dimensions, surface form, and surface finish or texture. “Traditional” subtractive manufacturing methods (i.e. machining) generate a desired geometry through removal of stock material using a cutting tool whose location is controlled by the machine’s motion platform. To first order, dimensional geometry errors are driven by the accuracy of the machine tool, while tool interactions with the workpiece tend to control the surface finish generated by machining. The location of the tool can be predicted through

machine modeling [3,4]. We can express the actual location of the tool as a vector function:

$$\mathbf{r}_{act} = \mathbf{r}_{nom} + \delta$$
$$\delta = f(x, y, z)$$
(1)

where $\mathbf{r}$ and δ are vectors, and the subscripts denote actual position or nominal position. The generated part geometry is generally considered to be deterministic based on the tool location.

In additive manufacturing, however, the manufacturing system deposits material at a desired location, building onto existing materials and structures. Final part geometry becomes an outcome of the positioning accuracy of material placement, the physics of the deposition and fusing processes at each material location, the deformation from residual material stresses, and the cumulative errors of the build process. As a result, additive deposition process and interactions provide a substantial contribution to geometrical accuracy which varies with location and orientation within a part volume. While machine characterization and metrology remains crucial for additive process control, it is not adequate or practical for an “a priori” deterministic analysis of geometrical accuracy as in conventional machining processes. Figure 1 illustrates the issue of design intent versus

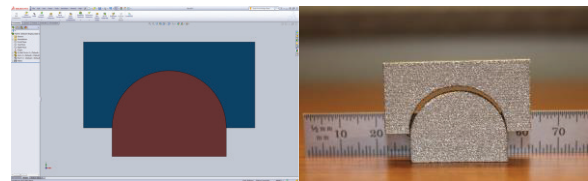


FIGURE 1. The design of an arch and semicircle intended for assembly. The part at right (fabricated on an Arcam machine)¹ had minimal post-processing.

¹ Certain commercial equipment, instruments, materials, or software are identified in this paper in order to adequately

actual manufactured part in AM.

EXPERIMENTAL METHODS

Similar to the approach by Moylan and others [5], we have designed test artifacts intended to exercise the capabilities of either plastic or metal additive manufacturing methods by anyone; i.e. OEMs, service bureaus, or end users. The value of artifacts is that they provide a predictive guide for the designer, thus, minimizing the effort required in post-fabrication inspection. In order to adequately meet geometry requirements for designers (as expressed in [6]), we need to assess minimum resolution, relative accuracy of form and size, surface texture; and anisotropies associated with orientation or workspace location. Graphical techniques, similar to Stedman plots [7] for surface texture instruments are useful to evaluate and compare the suitability of additive manufacturing methods.

Our initial method is to determine positional accuracy throughout the workspace. This can be tested by designing a part that has geometric features spanning the working volume of the machine. A simple geometry that we designed is a prismatic structure, dubbed “Manhattan”, as shown in Figure 1. The planar faces can be evaluated for both position and form, and the intersections of the planar faces create point locations that can be evaluated against the original design. The size of the artifact can be scaled in x, y or z as desired to fill the machine work volume of interest.

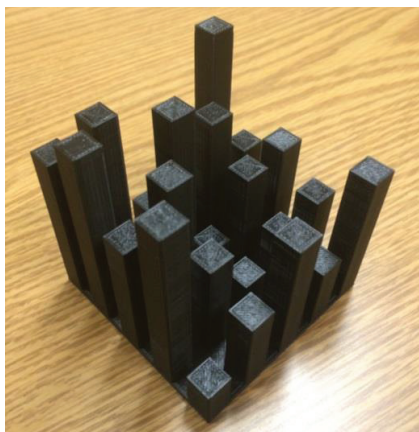


FIGURE 2. Manhattan test artifact structure. This artifact and those shown in Figures 5 and 7 were made on a Makerbot Replicator 2.

describe the experimental procedure. Such identification does not imply recommendation by the authors, Sandia National Laboratories, or Honeywell Federal Manufacturing and Technologies.

Using a Manhattan structure fabricated on an Objet 30 Desktop printer, we use a coordinate measuring machine (CMM) to measure the location of the vertices of 9 of the 25 “high-rise” structures. We plot the deviations of the locations as vectors, based on nominal locations in Figure 3. Work remains to decouple feature geometry and process influences from machine performance characteristics.

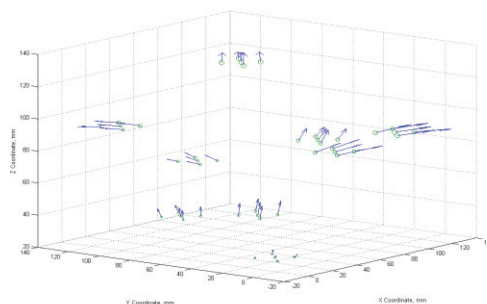


FIGURE 3. Vector plot of deviations for an “as-built” Manhattan; scaled to approximately 110 mm for the Objet workspace. The CMM was a Zeiss UPMC 550².

A non-graphical way of presenting the location deviations would be to use an evaluation method similar to the ISO 10360-2 MPE_E [8]. Results for these evaluations fabricated in stainless steel on an Arcam A2X electron beam melting system and on an EOS EOSINT M280 direct metal laser sintering system will be presented. Figure 4 shows a histogram of the

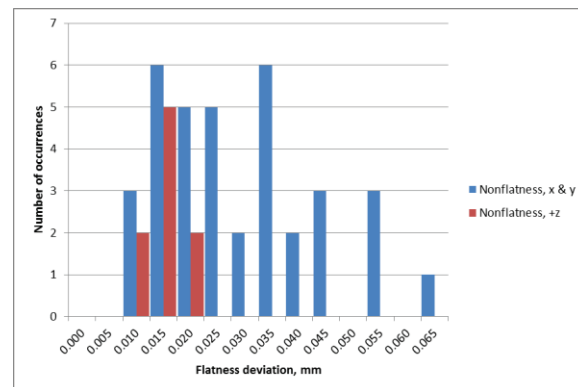


FIGURE 4. Histogram of evaluated flatness deviations for 9 of the high rise columns. Without performing a Chi-square test, the histogram hints that the +z axis has better geometry control than x or y axes.

² The authors thank Tyrell Lorenzo for his work on the CMM and Brad Salzbrener for his work with the Objet 30, both of Sandia National Laboratories.

variations in form (defined using flatness) in x, y and z on the Manhattan part built on the Objet.

We have also designed polyhedral structures, as shown in Figure 5, to test for anisotropies in surface texture of the finished part. It should be noted that when measuring surface texture, it is important to measure multiple texture parameters. The “S” family of parameters (areal texture) provide more information than the R parameters. In particular, spatial parameters Ssk (skewness), Sku (kurtosis), Str (degree of anisotropy) and Std (texture or lay direction) can be used, in addition to the more frequently used texture parameters such as Sa and Sq. Figure 6 shows an areal image indicating a strongly anisotropic texture for a part manufactured on a Makerbot Replicator 2.

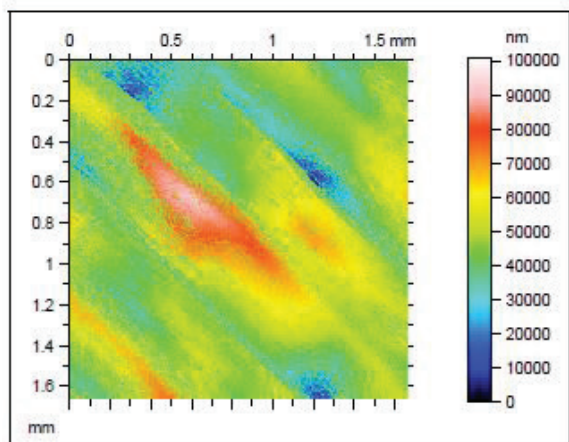


FIGURE 6. Measurement and evaluation of a flat surface (+z direction) from a Makerbot, measured on Taylor-Hobson CCI-Lite scanning interferometer, 10x objective; texture evaluations using Talymap (MountainsMap) v6.

Another design is a three-dimensional Siemens star [9], illustrated in Figure 7. The Siemens star allows determination of minimum printable feature resolution, and possibly the ability to measure a “printable feature” evaluation, along the lines of characterizing a modulation transfer function (MTF) used in 2D imaging systems such as optics or paper printers.

Our preliminary evaluation indicates that these types of tests will provide the designer with a good model of the dimensional accuracy capabilities of additive manufacturing systems, and will reduce the design iteration necessary to achieve desired functional geometry with additive manufacturing.

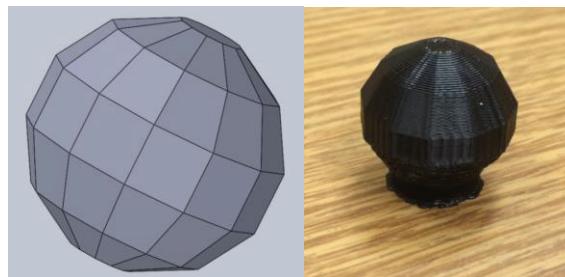


FIGURE 5. Sixty-two sided polyhedron test artifact structure.

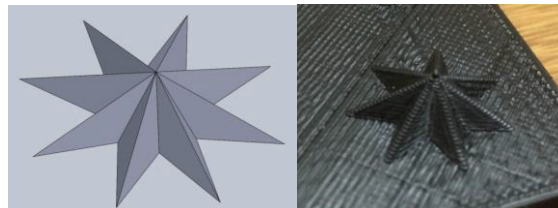


FIGURE 6. Siemens star artifact structure, altered for 3-dimensional testing.

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Characterizing additive manufacturing parts using coherence scanning interferometry

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INTRODUCTION

Additive manufacturing (AM) is increasingly being used to produce fully functional parts [1]. With this shift in emphasis from “just a prototype”, tolerances for critical dimensions and surface finish can take on critical importance, particularly for applications having strict requirements in this regard. It is therefore vital to develop methods to characterize AM parts to ensure adequate performance or inform/verify post-processing steps.

Coherence scanning interferometry (CSI) provides non-contact areal topography maps with typical single-measurement topography repeatability of less than a nm on smooth, high-reflectivity surfaces [2]-[3], and has been validated relative to stylus metrology using roughness standards [4]. However, in the past CSI has been challenged by AM materials: they can have very rough surface finish with local slopes well beyond the specular limit, and for the case of plastics are often diffuse, translucent, or porous. These properties can significantly suppress the strength of any interferometric signals.

With recent advances, CSI offers significantly improved sensitivity and is now well suited for characterizing additive manufactured parts, as demonstrated in this paper.

MEASUREMENT & ANALYSIS

A variety of unfinished 3D-printed parts were measured using a modern commercial CSI microscope [4]. For these experiments, the baseline data acquisition time is about 0.14 seconds per micron scanned. Where indicated, dynamic noise reduction (DNR) was used to detect particularly weak signals. DNR allows a user-specified trade-off between throughput and sensitivity with no other performance sacrifice.

All surface plots shown represent raw height data without smoothing, masking or interpolation of missing data points.

3D-PRINTED PLASTIC PARTS

3D-printed plastic parts were measured with a 2.5X Michelson objective. This objective offers a relatively large field of view (FOV) of up to ~7-mm square with the classic tradeoff of relatively low NA (0.075), meaning that measuring slopes beyond ~4° requires detecting scattered light.

FIGURE 1 shows a nominally flat surface of a polycarbonate test chip, oriented along the layering direction. A strong undulation is present with period corresponding to the layer thickness (~175 μm) and peak-to-trough amplitude of ~50 μm . Data coverage is near-complete despite weak material reflectivity and local slopes up to ~50°.

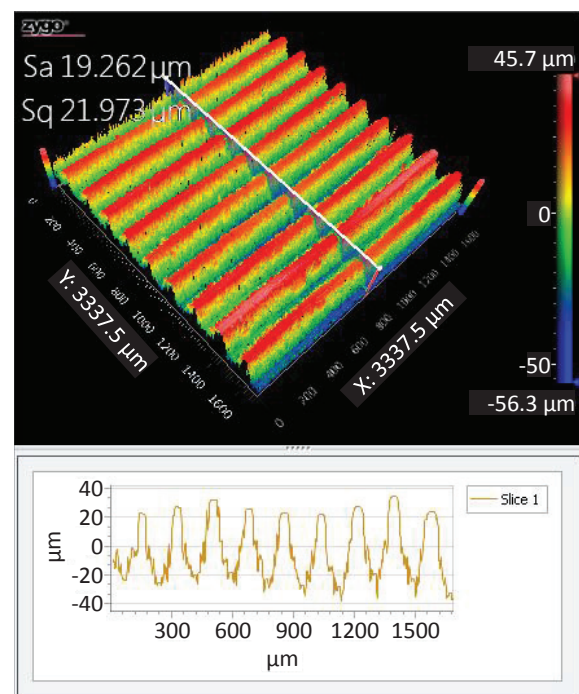


FIGURE 1. Layering-direction surface of 3D-printed polycarbonate coupon.

FIGURE 2 shows a nominally-flat surface of 3D-printed VeroClear [6], oriented normal to the layering direction. This sample represents a commercial-grade “best effort” to produce a smooth surface without finishing. Manufacturing

artifacts are obvious, most notably an array of dome-like features with a height $\sim 10\text{ }\mu\text{m}$ and periods of $\sim 250\text{ }\mu\text{m}$ and $\sim 500\text{ }\mu\text{m}$ along the X- and Y- axes.

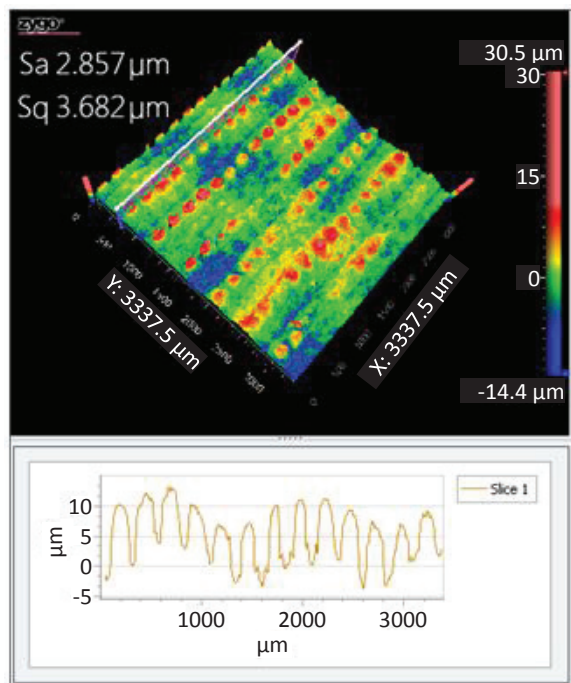


FIGURE 2. Layering-normal VeroClear surface.

Finally, FIGURE 3 shows a raised square pad in a probe baseplate made of VeroClear, measured in a single field (no stitching). Nominal side-length is 4.5 mm, nominal pad-height is 250 μm , and all surfaces are designed to be flat. The measured step is closer to 275 μm . Insets for top and bottom surfaces show surface roughness on a 10- μm scale, with artifacts similar to those seen in FIGURE 2.

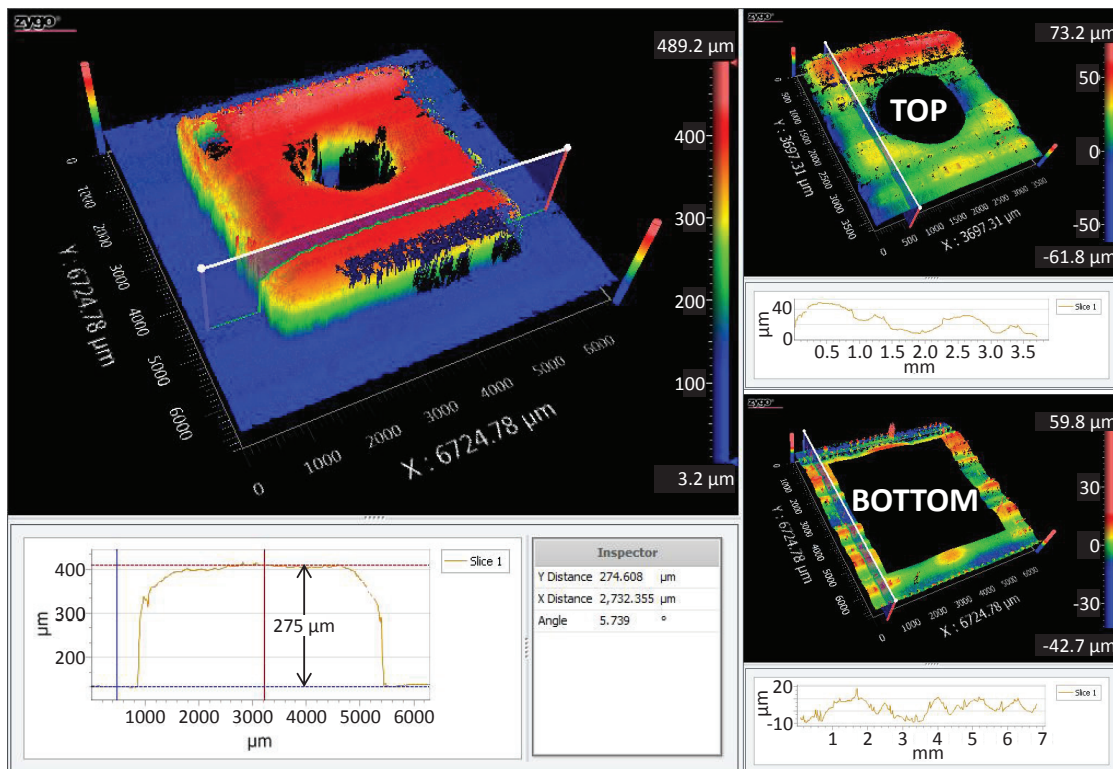


FIGURE 3. Nominally-flat square pad of a probe baseplate produced with 3D-printed VeroClear.

3D-PRINTED METAL PARTS

Stainless steel test parts were fabricated using Direct Metal Laser Sintering (DMLS) [7] by an external vendor with no post-processing (i.e., raw finish); an example is shown in FIGURE 4. Nominal layer thickness was intended to be $20\text{ }\mu\text{m}$, although this was discovered to not be the case.

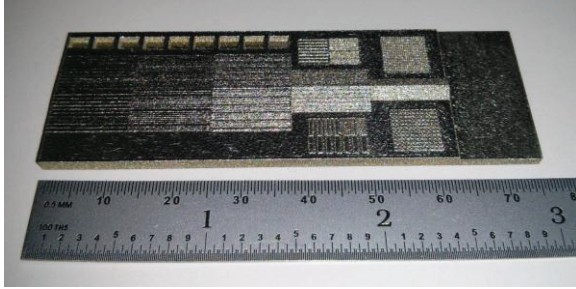


FIGURE 4. 3D-printed stainless-steel part manufactured using DMLS.

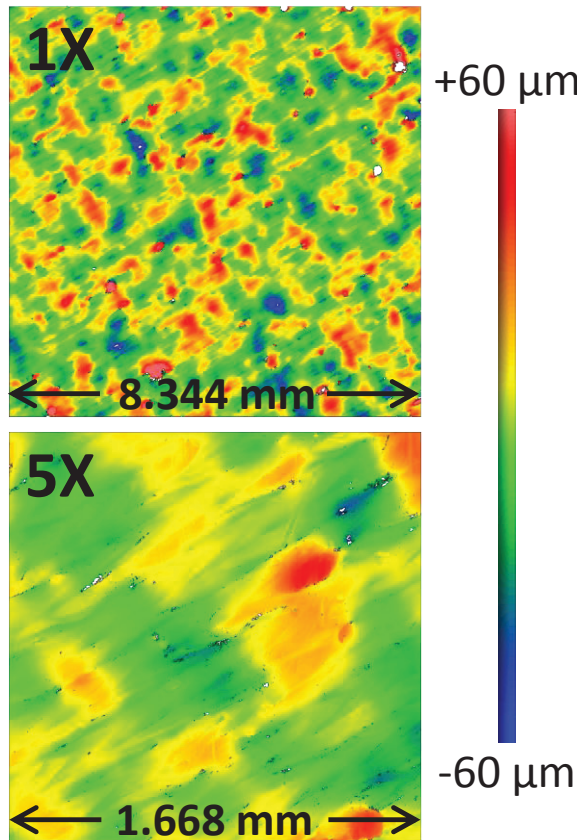


FIGURE 5. Nominally flat region of DMLS part as measured with 1X and 5X Michelson objectives.

To assess roughness intrinsic to the DMLS process, measurements were made over an unpatterned region comprising a nominally flat surface oriented normal to the layering direction.

Two Michelson interference objectives were used: a 1X and a 5X, the latter of which is frequently used as a reference objective for surface-texture characterization on high-precision functional machined parts (e.g., sealing surfaces in high-pressure injectors). Dynamic Noise Reduction (with a 4X increase over baseline measurement time) was used to achieve near-complete data coverage. Resulting surface maps are shown in FIGURE 5.

For the 1X-Michelson data, unfiltered S_q is $17.7\text{ }\mu\text{m}$, compared with $12.1\text{ }\mu\text{m}$ for the 5X Michelson. A more detailed comparison of the spatial-frequency contents of each map are represented by the power-spectral-density (PSD) plots in FIGURE 6. The curves represent 2D spectra collapsed to a single dimension, scaled such that total integrated power corresponds to S_q^2 .

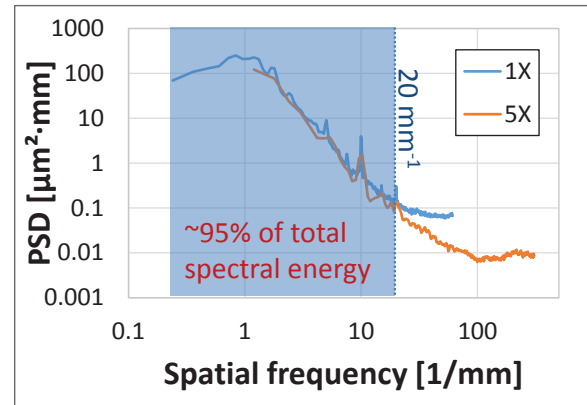


FIGURE 6. PSD plots for nominally flat surface of DMLS part as measured by 1X and 5X Michelson objectives.

TABLE 1. Roughness parameters with and without low-pass filtering for cut-off frequency 20 mm^{-1} .

Parameter	1X Michelson	5X Michelson
Raw S_q	$17.7\text{ }\mu\text{m}$	$12.1\text{ }\mu\text{m}$
Raw S_a	$14.0\text{ }\mu\text{m}$	$11.8\text{ }\mu\text{m}$
Filtered S_q	$17.4\text{ }\mu\text{m}$	$9.4\text{ }\mu\text{m}$
Filtered S_a	$13.7\text{ }\mu\text{m}$	$9.2\text{ }\mu\text{m}$

The PSD curves agree well up to $\sim 20\text{ mm}^{-1}$, above which a discrepancy emerges, possibly due to aliasing effects with higher frequencies in the 1X data. That said, the PSD is dominated by spatial frequencies below this frequency: as can be seen from the relative values of S_q in TABLE 1, low-pass filtering to a 20 mm^{-1} cut-off captures 95% of the total spectral energy.

Thus the 1X Michelson is well-suited for capturing the PSD of this unfinished surface, while also covering $\sim 70 \text{ mm}^2$ in a single FOV. This showcases a key strength of CSI: operation at low NA and large FOV is limited only by the available optics and retains full vertical resolution.

The observed intrinsic roughness was surprising at first: certainly moderate roughness was expected given the unfinished surface, but not rivaling the supposed layer thickness of $20 \mu\text{m}$. This apparent discrepancy was resolved through a measurement of a staircase structure designed with step-heights of $20 \mu\text{m}$, using the 1X Michelson over its full FOV of 16.6-mm-square along with 4X DNR (16X increase over baseline measurement time).

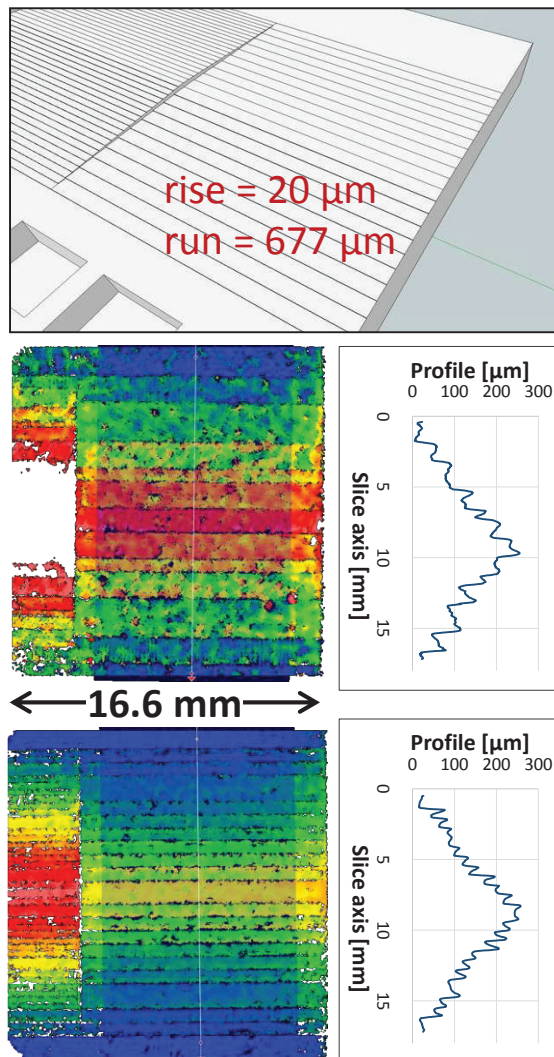


FIGURE 7. Staircase with $20\mu\text{m}$ steps in custom part. Top: as designed. Middle: as printed with inadvertent $40\text{-}\mu\text{m}$ layering. Bottom: as printed with correct $20\text{-}\mu\text{m}$ layering.

As shown in FIGURE 7, the design comprises steps with a rise of $20 \mu\text{m}$ and a run of $677 \mu\text{m}$. Measuring the DMLS part at this location reveals roughness that almost obscures the step pattern. With heavy averaging along the staircase, enabled by the large-area measurement, it emerges that only about half the expected number of steps are present.

These data were shared with the vendor, who confirmed the inadvertent usage of $40\text{-}\mu\text{m}$ layering and promptly produced a replacement part with $20\text{-}\mu\text{m}$ layering. A corresponding measurement of this part is shown at the bottom of FIGURE 7.

CONCLUSION

Characterizing the critical dimensions and surface finish of AM parts will become increasingly important, particularly for full-function applications. State-of-the-art CSI can measure these parts with nm-scale vertical resolution, even with their challenges of weakly-reflecting surfaces and high local slopes. This could in turn enable AM users to monitor and refine their process to minimize post-processing and material costs.

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CHARACTERIZATION OF ADDITIVE MANUFACTURED SURFACES WITH CONFOCAL MICROSCOPY

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ABSTRACT

The specific surface structure of additive manufactured parts causes difficulties when using the popular tactile profilometry method. Therefore, this study shows the potential of a new approach by an optical measurement system including areal parameters. A special focus within this study is the classification of the orange peel severity – a common issue in laser-sintering.

INTRODUCTION

Additive Manufacturing (AM) shows a high potential to meet the requirements of the increasing time and cost dominated product development process (“lean development”). Furthermore, new industrial trends like bionics, lightweight construction or “mass customization” are potential fields of application for AM [1]. Regarding these developments, it is important that the part quality meets the customer needs. Concerning the functionality of a component, surface texture plays a significant role, because surface effects in general cause up to 10 % of manufactured part’s failing rate [2]. With respect to the laser-sintering process, as a popular AM technology, this value is estimated to be even higher and therefore bad surface quality is one of the main constraints concerning this technology [3].

Compared to traditional manufacturing techniques, such as milling or drilling, the laser sintering is characterized by a layer-wise part production without any tools. In a first step, a polymer powder is randomly disposed on a building platform. After a preheating process, a laser beam melts selective areas of the later parts, whose CAD-models have been sliced into many single layers before the process. When one of these layers has been sintered, the building platform is lowered by one step and new powder is disposed. By repeating these steps, solid parts are manufactured, layer by layer.

As a consequence of the above mentioned production sequence, the surfaces of laser-sintered parts are on the one hand characterized by an aperiodic profile, caused by the random powder disposal and on the other hand they feature the so called “staircase effect”, due to the layer-wise production. Additionally, a third effect called “orange peel” appears, when powder, which has not been melted by the laser beam at the first time, is recycled (by mixing with fresh powder) for the reuse in later processes – which is a common practice due to high raw material costs.

STATE OF THE ART

Technical literature contains several analyses concerning the surface structure of AM parts and how it is affected by the laser-sintering process. Parameters like the part orientation, the layer thickness, the outline laser energy density and the fill scan spacing have been identified as significant influencing factors on the surface roughness [4] [5] [6] [7] [8]. With a focus on the effect of orange peel, several studies identified the powder age (described by the particle size, the molecular weight, the polymer chain length or the melt viscosity rate) [9] [10] [11] [12] and also the surface orientation [13] as reasons for this phenomenon. Furthermore, mathematical models have been developed to predict the surface roughness of AM parts [14] [15] and the possibilities of a surface structure optimization by post-processing have been investigated [16]. All the above mentioned analyses and models have in common that the surface structure is measured by tactile profilometry. Analyzing an external surface with this technology means scanning the test specimen laterally with a diamond stylus and measuring the vertical displacements as a function of horizontal movement. The result is a single surface profile which allows the calculation of surface parameters concerning this line. Due to the surface characteristics of AM parts, each variation of the

measurement position is equal to a significant variation of the parameter values. Even though the German VDI-Standard 3405 describes the tactile profilometry as a measurement technique, Wegner deduced that it is of limited suitability to describe surface structure effects, like the orange peel, of AM parts [12]. A general statement is given by Seewig who pointed out that a reasonable analysis of aperiodic surface structures with only one single profile line is not possible [17]. Furthermore, Leach pointed out that an areal measurement has a more statistical significance than an equivalent profile measurement and is a closer representation of the “real surface” [18]. The same conclusion, concerned to laser-sintering as special manufacturing technique, is reported by Lonardo, who used an optical conoscopy because a stylus instrument is not suitable for the AM parts surface characteristics [19]. The conoscopy instrument Lonardo used had a z-accuracy of 6 μm . Even though he managed to avoid the disadvantages of a stylus instrument, his measurement technique was relatively imprecise. Furthermore he concluded that the reliability of the measures depends on the optical properties of the surface and its slope.

Only a few other known studies used an areal measurement technique to describe AM surfaces: Hornfleck used a confocal microscope to measure R_z values of parts which were produced by the fused deposition modeling [20], another AM technique with periodic surface profiles in contrast to the powder based processes. Kühnlein used a confocal-laserscanning-microscope to analyze R_z values as well. He focused on the mask-sintering process which is another powder based AM technique. He compared the measured values to a tactile profilometry and reported a huge difference between $R_z \text{ Laserscan} = 200 \mu\text{m}$ and $R_z \text{ Profilometry} = 30 \mu\text{m}$, and explained this with a higher resolution of the confocal-laserscanning-microscope [21].

The above mentioned studies concerning the orange peel severity are even one step behind, because the effect is described by a subjective optical inspection and a classification in groups or a scoring system without numerical parameters. Only one known study quantifies the orange peel effect by measured values: Yusoff constituted certain values of surface roughness (R_a/R_z) to certain degrees of orange peel severity [22]. He determined a degree of a “good” orange peel effect for R_a values lower than 10 μm ,

a “mild orange peel” for R_a values between 10 and 14 μm and “orange peel” for R_a values higher than 14 μm . However, he too measured the surface parameter values by tactile profilometry, and used a scan length of only 3 mm.

Drawing a conclusion out of the known studies and the problems caused by the used measurement techniques concerning the surface characteristics of AM parts, the goal of the study performed was to evaluate the different possibilities of the confocal microscopy for a surface quality control in AM, with a special focus on the orange peel severity and the staircase effect.

The core of a NanoFocus μsurf confocal microscope used in this study is an integrated confocal-optical filter unit, the multi-pinhole-disc (MPD). It is combined with a high-precision focusing module [23]. The light of an LED source is focused through the MPD and the objective lens on to the sample surface, which reflects the light (FIGURE 1).

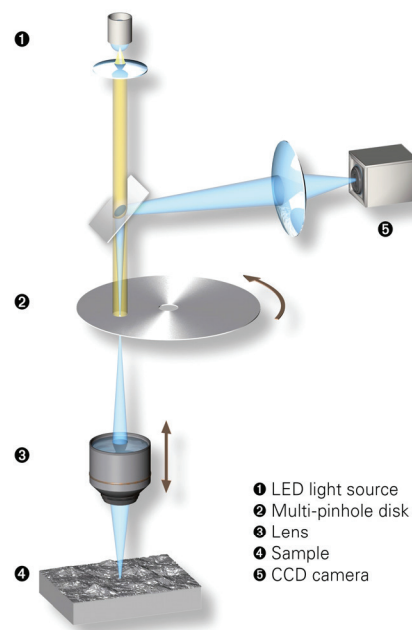


FIGURE 1. Schematic illustration of the confocal microscopy.

Reflected light from out of focus areas is filtered by the pinholes of the MPD. Thus only in-focus light reaches the CCD camera. This enables the confocal microscope to reach a high vertical resolution in the nanometer range. Each confocal image is a horizontal slice through the topography of the sample. Capturing the images at

different focal heights produces a stack of such images, achieved through precise vertical displacement of the objective lens.

In contrast to scanning electron microscopy (SEM), for example, confocal surface measurement produces data as real height coordinates (x , y , z). Only with this quantitative information it is possible to achieve exact evaluation of 3D parameters which make it possible to obtain much more meaningful results. In addition, there is no need for the samples to be prepared. An optical system also offers advantages compared to atomic force microscopes, such as large measurement areas, high speed and non-contact operation.

By using an optical, areal surface measurement technique, it is possible to analyze a large number of profile lines within the scanned area to determine the traditional profile parameters such as R_a , R_z , etc. Furthermore, the surface can be characterized in accordance to new areal parameters like S_a , S_q , etc., which are defined in ISO 25178-2 and -3.

EXPERIMENTAL SETUP

As reported in former analyses, the effect of orange peel depends on the surface orientation in the manufacturing process. Therefore, test specimens were developed to cover a wide range of surface orientations within one part (FIGURE 2). The different specimens were built from polyamide and polypropylene powder on different laser-sintering machines (EOS Formiga P100 and DTM Sinterstation 2500 HS).

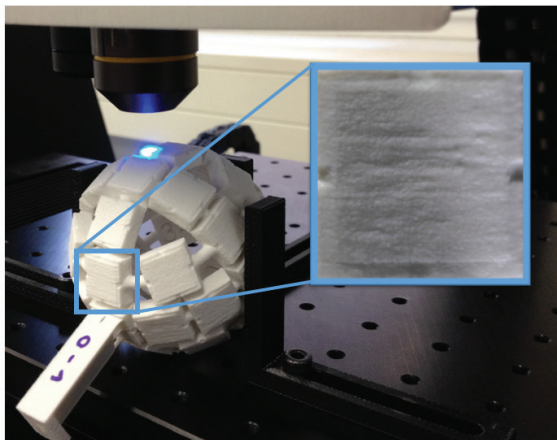


FIGURE 2. Test specimen during confocal microscopy. Inset: Orange peel effect.

Each surface orientation was analyzed using a μ surf confocal microscope from NanoFocus, with a 10×0.3 objective and an areal test field of $10 \times 10 \text{ mm}^2$.

Furthermore a subjective evaluation of each single surface with a special focus on the orange peel severity was done by laser-sintering experts. This evaluation was based on grades from 1 (no orange peel effect) to 6 (extreme orange peel effect), and the mean values from all experts were used for the following correlation.

Eventually, a tactile measurement of laser-sintered cuboids (see inset in FIGURE 3) with 20 profiles per each single surface was realized in order to evaluate the common state-of-the art method as well. A Mitutoyo Surftest SJ-400 was used for these measurements and a lateral displacement of 0.1 mm between the measurement positions was chosen (tip radius $5 \mu\text{m}$, sampling length 2.5 mm, cut off length 2.5 mm, scan length 12.5 mm).

RESULT AND DISCUSSION

On account of the unique characteristics of each single measurement of the tactile profilometry, it is obvious that the more profiles are analyzed, the wider the range of each surface parameter value becomes. The analysis with 20 profiles (FIGURE 3) showed, in comparison to just a few profile measurements -as it is often described in the state of the art- a significant increase of parameter range and also an increase of the relative standard deviation, for example up to 43 % relating to W_z .

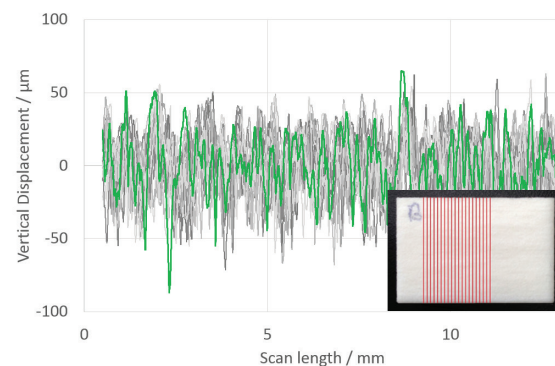


FIGURE 3. Overlap of surface profiles of a test specimen, measured with tactile profilometry. One single profile is highlighted. Inset: Variation of profile lines within the surface of the test specimen.

Therefore, it is absolutely necessary to measure an adequate surface area to achieve a reliable analysis of an AM surface. Such an areal surface topography measured by the confocal microscopy is shown in FIGURE 4.

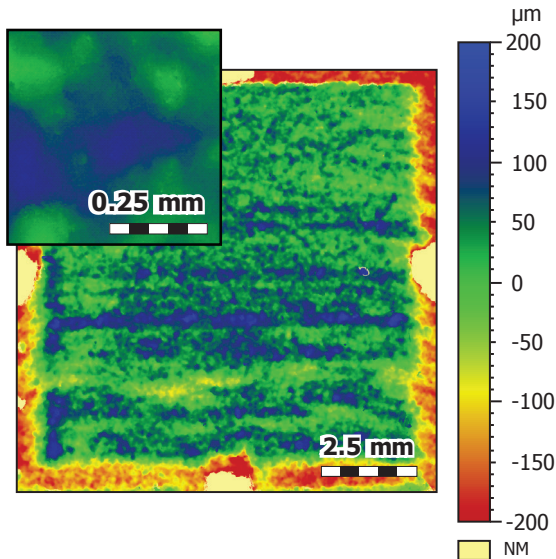


FIGURE 4. Laser-sintered topography measured with a confocal microscope. The inset illustrates the level of detail contained in the data set. The marks in the middle of each side of the test area are used for positioning.

The generation of such a huge field of areal data offers the possibility to evaluate more surface parameters compared to the measurement of single profile lines. Hence, a correlation analysis with regard to the orange peel effect was performed including classical parameters according to ISO 4287 as well as areal parameters defined by ISO 12781 and ISO 25178. In total, more than 90 different parameters in combination with various filters have been considered in an ANOVA.

TABLE 1 shows selected results of the analyses performed. At a first glance, a direct correlation between the orange peel severity and the build angle can be detected. For surfaces within the build plane and for nearly all upskin surfaces (build angle > 90°), almost no orange peel effects appear and therefore good grades were assigned. In contrast to that, vertical and downskin surfaces (build angle < 90°) seem to be more prone to this phenomenon.

Regarding the calculated significances of the ANOVA, the parameters W_a (Gaussian filter, 2.5 mm) (p-

value < 0.0001, $R^2=0.8784$) and $FLTq$ (Gaussian filter 0.25 mm) (p-value < 0.0001, $R^2=0.9012$) showed a correlation concerning the orange peel severity. W_a is defined in ISO 4287 as arithmetic average of the absolute values of the waviness profile and therefore it is an indication that the orange peel effect, which is characterized by a waviness all over the surface (compare inset in FIGURE 2), can be classified by this parameter. But it is important to mention that, within this study, 68 single profiles build the base for the classical parameter W_a . $FLTq$ is, as second significant parameter, defined in ISO 12781-1 and describes the root mean square flatness and can be a reasonable classification parameter as well, because a surface which is not characterized by an orange peel effect shows a much flatter topography than a peeled surface. At this point, there seems to be a fluent transition from shape deviation of 2nd order (waviness) to a deviation of 1st order (shape) when regarding the orange peel severity of AM parts.

TABLE 1. Test Specimen Surface Classification and selected Parameters.

Surface #	Grade of Orange Peel Severity	Build Angle [°]	W_a (Gauß 2.5mm) [μm]	$FLTq$ (Gauß 0.25mm) [μm]	R_a (Gauß 2.5 mm) [μm]
6	1	180	4,95	15,42	12,19
0	1,75	0	6,59	15,12	13,20
7	1,75	150	6,78	22,49	22,05
16	1,75	150	7,99	21,33	20,75
17	1,75	150	6,87	20,32	20,07
32	1,75	120	8,22	21,46	20,50
33	1,75	120	8,47	21,88	21,17
5	2	150	8,62	26,26	25,53
18	2	120	7,74	19,84	17,41
29	2	90	7,04	18,94	17,42
31	2	120	9,91	19,48	17,06
36	2	60	6,59	16,39	14,26
37	2	60	6,65	15,74	14,32
4	2,25	120	8,83	24,75	23,90
8	2,25	120	6,29	21,63	22,18
14	2,25	90	7,42	20,77	17,68
15	2,25	120	8,36	22,69	21,45
22	2,25	90	10,55	18,91	15,05
30	2,25	120	6,96	20,83	19,85
20	2,5	60	6,29	16,63	13,50
21	2,5	30	7,59	20,13	16,54
12	2,75	30	6,86	19,29	15,77
34	2,75	60	7,53	18,26	14,90
35	2,75	60	6,55	17,61	14,62
13	3	60	6,99	16,51	12,75
26	3,25	90	7,47	20,18	17,20
28	3,25	90	8,87	26,37	15,67
9	3,5	90	8,50	20,29	15,65
1	3,75	30	6,88	19,22	16,43
19	3,75	90	7,63	20,73	16,20
23	4	90	18,06	33,57	18,50
24	4,25	90	14,70	27,10	13,32
27	4,25	90	12,72	29,76	17,16
25	4,5	90	11,54	29,77	16,54
11	4,75	30	11,15	29,13	18,76
10	5,25	60	11,05	31,57	19,61
2	6	60	32,06	69,39	22,72

If we consider all orange peel surfaces with a grade worse than 4 as not acceptable, a limit of 10 μm for W_a and 27 μm for $FLTq$ can be considered at this first glance.

The classification of an orange peel effect by the parameter R_a , suggested by Yusoff [22] could not be validated (calculated p-value of 0.5581, $R^2=0.3702$). As shown in TABLE 1, the values of the test specimen were on a general higher level, caused by the higher resolution of the confocal microscopy in contrast to the tactile profilometry Yusoff used. But also without considering the quantitative values, a correlation could not be validated due to wide parameter ranges within one orange peel severity classification.

Considering the staircase effect as another AM phenomenon, the parameter Str was detected as significant classifier. Str (texture aspect ratio) measures the spatial isotropy of the surface texture. Therefore, the value for surfaces with a dominant lay, e.g. the staircase effect, tends towards 0 (FIGURE 5, Surface 07). Surfaces with an aperiodic texture show significant higher values (FIGURE 5, Surface 00).

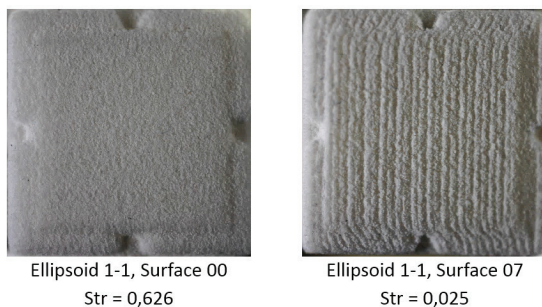


FIGURE 5. Test specimen surfaces with (right) and without (left) staircase effect and their corresponding texture aspect ratio (Str).

However, the texture aspect ratio shows a potential significance concerning the staircase effect: future analyses are still necessary, with special regard to the evaluation algorithms of this spatial parameter.

At last, regarding the classical surface parameters such as R_a or R_z , the statement of Leach [18] can be proved, because an optical areal measurement enables a higher statistical validation when analyzing AM surfaces. E.g. the relative standard deviation of R_a for the confocal microscopy based on 68 single profiles within this study shows a value of 13.3 % and is therefore almost three times higher than the relative standard deviation of the tactile profilometry using 20 single profiles and showing a value of 4.7 %. This is another significant indicator for the aperiodic surface structure of AM parts.

CONCLUSION AND OUTLOOK

The specific surface characteristics of AM parts need special analysis techniques and parameters. Within this study, it was proved that an optical 3D topography measurement, realized with a confocal microscope, offers the opportunities of:

- A higher statistical significance compared to the state of the art tactile profilometry.
- The quantification of the orange peel severity by the surface parameters W_a und $FLTq$.
- The characterization of the staircase effect by the texture aspect ratio.

However, future investigations are intended to ensure the proposed correlations. Therefore the authors will intensify the analysis of areal parameters measured with a confocal microscope.

Furthermore, AM metal parts, build by the laser beam melting process, will be analyzed as well, so the project will lead to a robust quantification of the external surfaces of AM parts. An automated inspection process will complete this new approach to make a further step towards quality assurance (QA) in AM.

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Effect of Direct Slicing on Geometric Tolerances in Additive Manufacturing Process

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INTRODUCTION

Additive Manufacturing (AM) parts and surfaces are inherently subject to stair case effect which can be quantified by cusp height. Cusp height of a layer is the maximum distance measured along a surface normal between the ideal surface and the produced layer. Although calculation of local cusp high is a simple task but estimating the overall deviation zone of the produced surface is a highly nonlinear and complicated problem. This paper presents a practical approach to predict the actual profile tolerances of the surfaces. This prediction is used to allocate profile tolerances for the additive manufacturing processes. Also the methodology can be used to select the optimum uniform layer thicknesses that compromise between the number of layers and the desired accuracy of the final surfaces. The unified developed methodologies are capable to analyse complex surfaces and geometries. Variety of experiments is carried out to study the effectiveness and practicality of the presented methodology. The developed methodology can be employed efficiently during design of rapid prototyping parts to compromise between final part accuracy and prototyping cost.

Problem Definition

The slicing process is a highly critical stage in Rapid Prototyping manufacture. As it can be seen in Figure 1, large thickness of slices generally incorporates for rough surface quality due to the stair-case effect and its corresponding cusp height in layered manufacturing. Alternatively, utilizing very small thickness of layers takes much longer time to finish a part and is costly. Although the desired layer thickness can be selected in majority of today's RP machines, but usually it remains constant for the entire model.

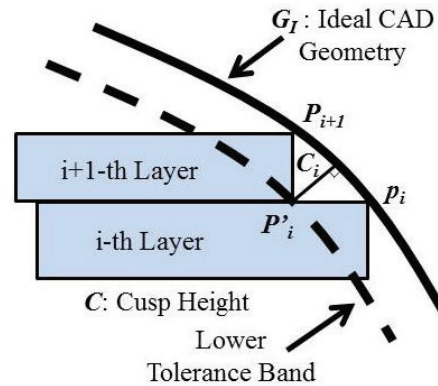


FIGURE 1. Cusp height and staircase effect

The actual cusp height can be calculated by geometric analysis of the two consecutive layers and the ideal Geometry, G_I . As it can be seen in Figure 1, for any corner intersection point, p'_j , of i -th layer and $i+1$ -th layer in any given orientation two corresponding intersection points, p_j and p_{j+1} , of the two layers and the ideal geometry can be found. The corresponding cusp height in the plan specified by three points of p'_j , p_j , and p_{j+1} is calculated by:

$$c_j = p'_j \overset{p_{j+1}}{p_j} \ominus G_I \quad (1)$$

where the operator $\overset{p_{j+1}}{p_j} \ominus$ specifies the Euclidian distance of point, p'_j , to the geometry, G_I , in a plane that the point, p'_j , forms with two points of p_j and p_{j+1} . As it can be seen, large thickness of layers generally incorporates for rough surface quality due to the stair-case effect and its corresponding cusp height in layered manufacturing. Alternatively, utilizing very small thickness of layers takes much longer time to finish a part and is costly. These two contradictions have led to research toward optimizing the layer thickness and improving the slicing techniques. However, the cusp height always depends on the surface tangent of the ideal geometry and the slicing techniques need

to be developed and customized based on the specifications of the ideal geometry.

Cusp height is commonly addressed in the literature as a major indicator of the accuracy of the final AM surfaces [1-5]. However, it can be used to study the local deviations of the points from the ideal geometry but understanding the global deviation zone of the produced surfaces need additional study.

A method to estimate the profile deviation zone for accurate allocation of the profile tolerances of the RP produced surfaces is presented in this paper. It is also shown that by the results of this methodological analysis can be used to select the optimum uniform layer thickness for the RP process. The presented methodologies are implemented for a unified solution using Non-Uniform Rational B-Spline (NURBS) representation of the surfaces. This will allows application of the developed procedure for both primitive as well as the sculptured surfaces. Case study of a NURBS surface is used for demonstration of the process and validation of the process.

Implementation

Variety of experiments are conducted to test and validate the developed methodology. In order to demonstrate the implementation of the presented methodology and for validation a case-study is presented here.

The ideal surface geometry is defined as a uniform, non-periodic NURBS surface generated by a control net including 36 control points defined identically in the two parametric directions. The degrees of NURBS surface in the parametric directions are identical and are equal to three (fourth order polynomials). The designed NURBS surface is presented in Figure 2.

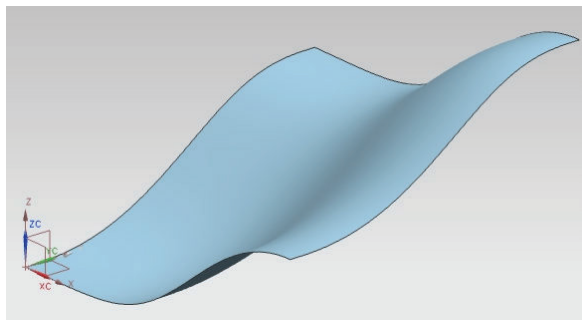


FIGURE 2. NURBS representation of the desired geometry

Figure 3 presents the results of the analysis:

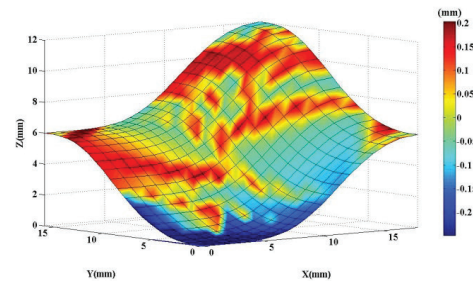


FIGURE 3. Estimated Distribution of the detailed Minimum Deviation Zone

CONCLUSION

Using the developed methodology the actual minimum deviation zone can be calculated and used directly to allocate profile tolerances for the designed surfaces. This methodology also can be adopted by the rapid prototyping slicing software to select the most appropriate uniform layer thickness that although doesn't increase the number of layers significantly, but it provides a much higher product's accuracy comparing to slicing with maximum layer thickness.

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DESIGN OF DYNAMIC FOCUSING UNIT FOR 3D LASER SCANNER

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INTRODUCTION

Laser scanning system has been broadly applied on laser material processing such as drilling, polishing, and additive processing. Currently, several types of laser scanning system have been applied on Selective Laser Sintering (SLS) based machine and that of spot size is essential for accuracy and quality of final product. To keep the same size of focusing spot in the entire objective flat field, a dynamic focusing unit which compensates the defocusing error is necessary. [1] Figure 1 shows the mechanism of compensation.

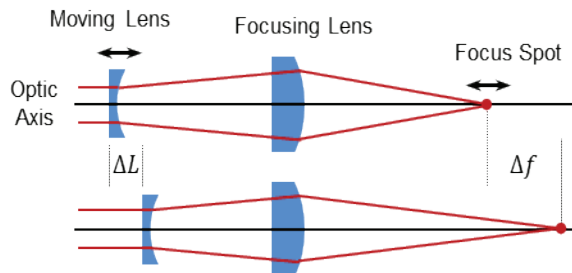


FIGURE 1. Dynamic compensation of defocus error

Previous studies [2,3] show that various methods were applied and this study focuses on the optomechanics. For this reason, an optimization is proposed by considering both mechanical and optical variables and constraints and tested with a prototype model.

DESIGN

The goal of design is to expedite the movement of the dynamic focusing unit which can increase the scanning speed, area, and accuracy simultaneously. The special field flattening optics with an f-theta objective lens can be a candidate but its flat field will be narrowed. For this reason a dynamic focusing unit with using

Voice Coil Motor (VCM) is proposed and Figure 2 shows that the design of that system.

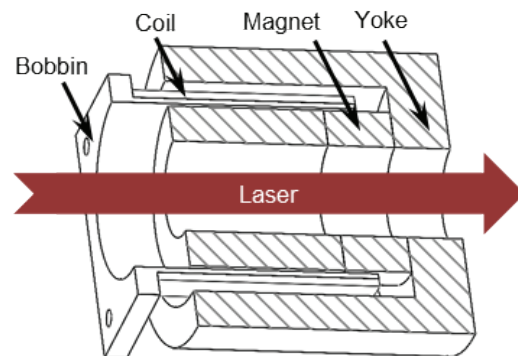


FIGURE 2. Elements of dynamic focusing unit

The focusing lens is fixed on the yoke and the moving lens is mounted on the bobbin. When the VCM is working, the bobbin is moving which means the moving lens is moving. The focused spot is moved in the range of VCM. For this reason, the lens system has to have large optical leveraging and the efficient VCM design is necessary.

DESIGN VARIABLES AND CONSTRAINTS

Optical Variables

The radius (R_1 , R_2) and thickness (t_1 , t_2) of each lens and initial distance (b) between moving lens and focusing lens are set as the variables in Figure 3. Those variables are co-related on the focal length and the focal point. If the lenses are selected from the same group, the focal point gets increased when the initial distance (b) is short. The focal length is set as 1300mm ~ 1400mm due to the design limitation. The stable spot size and enlarging optical leveraging are targeted.

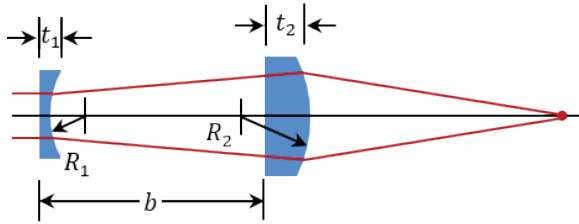


FIGURE 3. Schematic of optics

Mechanical Variables

The variables of voice coil motor are thickness of magnet and yoke, air gap length and coil diameter. Those decide the magnetic force which moves the bobbin of VCM, the indication of motor power, and the weight of the system. The objective function is a reciprocal of the acceleration and the optimal solution can be found by minimizing the function.

$$J = \min \left\{ \left(\frac{1}{F/m} \right)^2 \right\} \quad (1)$$

Equation 1 is the second order objective function for increasing the convergence of the solution. Afore mentioned variables are affected on the solution and the smallest solution of the objective function will be the optimal value of the variables.

Figure 4 shows the schematic of VCM design. The winding is not pointed out but the diameter has to be smaller than the gap.

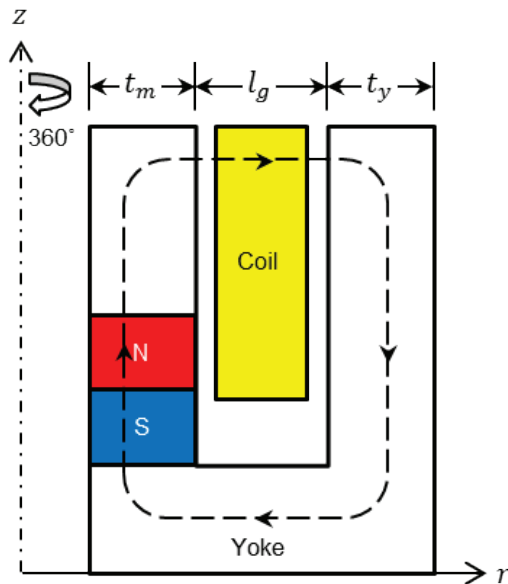


FIGURE 4. Schematic of VCM

Design Constraints

The location of focused laser spot is considered in the range of focal depth [4]. Figure 5 shows the laser beam and spot size. As an optomechanical constraint, the position resolution of voice coil motor must be in the range of the focal depth.

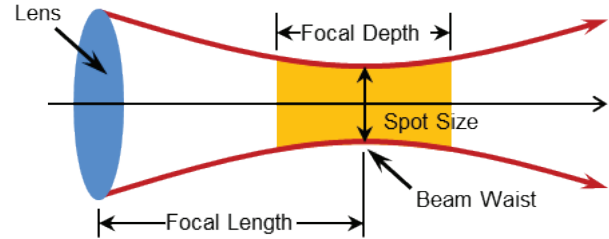


FIGURE 5. Focal depth and beam waist of laser beam

Several mechanical constraints are also proposed. The total size of the VCM has to be firstly considered for compactizing the focusing unit. The thickness of coil is also considered because it is attached on the bobbin. Finally, the current supply system has to be considered. The VCM operating current is set as 1A.

RESULTS

Optical optimization

The optical optimization has been made with using the ZEMAX, optical simulation software. The moving distance of VCM is set as 10 mm. The result shows that when the effective focal length of the moving lens and focus lens are 100 mm and 99 mm, respectively, the system focal length changes about 480 mm with maintaining the 100 μ m spot size through the whole VCM moving distance.

Mechanical optimization

The mechanical optimization which maximizes the magnetic force has been made with using the MAXWELL, magnetic field simulation software (in Figure 6), and sequential quadratic programming (SQP) algorithm in MATLAB Toolbox.

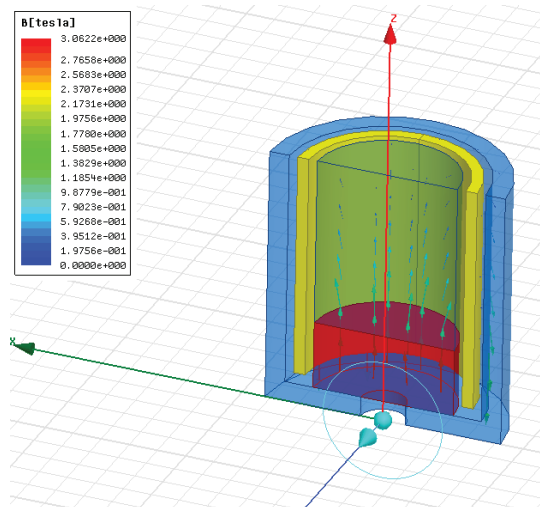


FIGURE 6. Magnetic field density in VCM by using Maxwell (magneto-static simulation tool)

The result shows that the thickness of magnet (t_m) is 8.5 mm, the thickness of gap (l_g) is 5 mm, and the thickness of yoke (t_y) is 3.5 mm. The bare coil diameter is 0.55 mm and the total number of coil turns is 218.

Experiments

By using the mechanical optimization result, a prototype system has been made. Figure 7 shows the test rig. In the rig, the VCM's motion is linearly guided by a linear motion (LM) guide.

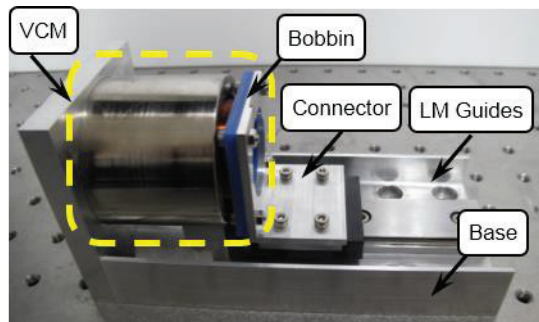


FIGURE 7. Positioning resolution test rig of dynamic focusing unit

The guide is has linear bushing, and rubber washer. Usual friction coefficient is 0.002 ~ 0.006. However, the linear motion cannot be secured because the asymmetric configuration of the LM guide. If one more LM guide is added to the opposite site of the LM guide, the rig can have the symmetric configuration. The symmetry can suppress the nonlinear motion, therefore, the test rig should be enhanced.

For measuring the resolution, a closed-loop control experimental setup is prepared and Figure 8 shows that.

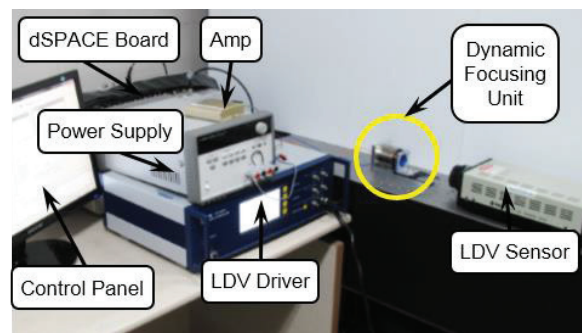


FIGURE 8. Experimental setup for measuring the resolution with closed loop control

The Laser Doppler Vibrometer (LDV) is used to measure the motion (Sensor : OFV-352, Driver : OFV-5000, Polytec GmbH). A pulse-width modulated signal is provided to VCM by a 4122Z VCM amplifier (Copley Controls Corp.)

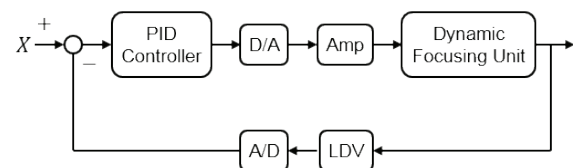


FIGURE 9. Block diagram for closed-loop control

The closed-loop control is shown in Figure 9 and the target displacement is set as input X. The error is measured by comparing the input and the result of measurement.

For real time closed-loop control, a DS2002/DS2003 A/D converter, DS2102 D/A converter, and DS1005 PPC boards (dSPACE) are chosen. A control panel is built by using MATLAB and dSPACE.

The resolution test shows that its resolution is 0.2 μm and Figure 10 shows that. If the symmetric configuration is added and PID gains are tuned more, the resolution can be finer than this.

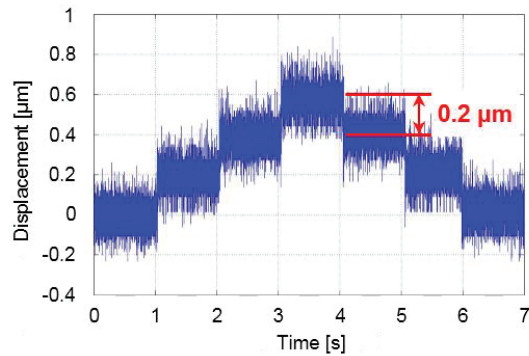


FIGURE 10. Positioning resolution of dynamic focusing unit

CONCLUSIONS

This work has shown that the new design of dynamic focusing unit can effectively increase the speed, area, and the dimensional accuracy by maintaining the spot size. The optimal design is proposed by considering the optical, mechanical variables and design constraints. A prototype test rig is also made and confirmed its resolution is 0.2 μm .

ACKNOWLEDGEMENT

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EFFECTIVE CALIBRATION AND IMPLEMENTATION OF GALVANOMETER SCANNERS AS APPLIED TO DIRECT METAL LASER SINTERING

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INTRODUCTION

Direct metal laser sintering (DMLS) is the most common process by which metal parts are presently being produced through an additive manufacturing approach. These laser processing systems generally utilize 2-axis galvanometer scanners as a means of manipulating the planar position of a laser spot to produce sintering of the powder bed. The dynamic positioning performance of the laser spot directly impacts the dimensional accuracy of each sintered layer and the final part dimensions. As the scanner is the primary means of creating relative motion between the laser spot and powder bed, calibration and characterization of the scanner's ability to position the laser spot is the best way of improving the dimensional accuracy of the finished sintered part.

Current methods used in the calibration of two-axis galvanometer laser scanners include several novel techniques, but the most effective and readily validated method involves the measuring of a part marked by the system. The "mark-and-measure" approach is the most reliable of current calibration methods because the output of the given process, a part marked in-situ, is the artifact onto which metrology is carried out.

This paper summarizes the findings of a case study on effective means of 2-D galvanometer scanner calibration performed at Aerotech Inc. The study explored the use of 2-D laser scanners used in combination with field flattening optics, F-Theta lenses, and the findings and results are not necessarily applicable to other laser scanner arrangements. The study was able to produce micron-level

static laser spot positioning accuracy over a large majority of the scanner's field of view.

MARK & MEASURE CALIBRATION

The mark-and-measure calibration technique is widely used in laser processing systems. The general procedure is to mark patterns on a material, measure the pattern in the global space, and to use the difference between each mark's desired and measured location as a correction factor in future commanded moves. In the specific procedure followed during the case study described herein, two separate systems were used. One was a marking station fitted with a particular Aerotech scanner to imitate its integration into a laser processing system, and the second was a separate machine vision inspection station used to measure the parts produced by the marking station. Both systems are shown below in Figure 1. Grid patterns were burned into substrates at the marking station, and then the substrates were moved to the machine vision system for inspection. The data taken by the inspection station were appropriately post processed and turned into a two dimensional error array for the purpose of implementation into a calibration file in the scanner's controller. A subsequent substrate was marked and measured to determine the effectiveness of the calibration file. This process was repeated iteratively to produce the best results.

Several factors associated with the consistency of the spatial relationship between the scanner, the laser, and the substrate, as well as aspects related to the interaction of the laser and the substrate during the marking process were found to affect the success of a scanner's calibration via this mark-and-measure methodology.

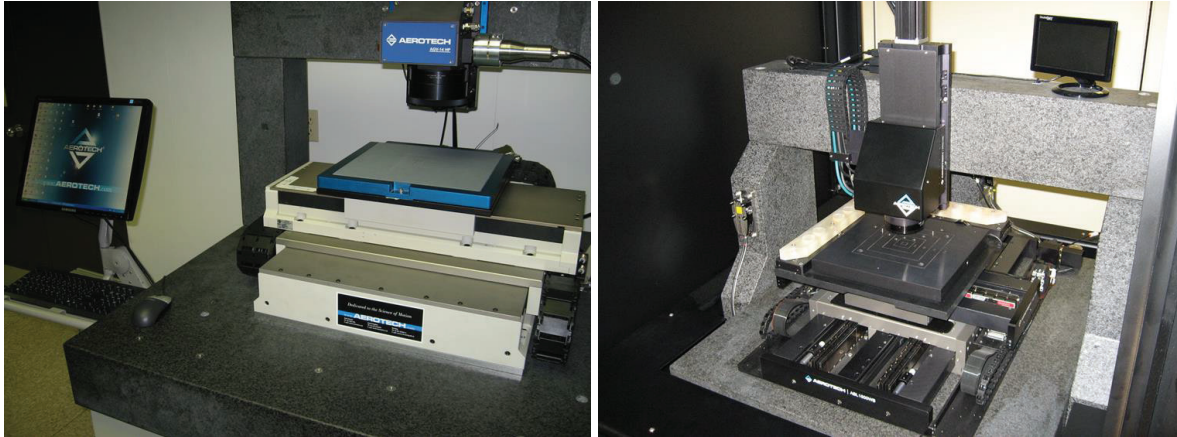


FIGURE 1. Images of the Laser Marking Station (left) and the Machine Vision Inspection Station (right) used in the laser scanner calibration case study.

ERROR SENSITIVITIES IN SCANNER SYSTEMS

The accurate and precise marking of substrates was found to be affected by several factors involving the physical setup of the marking station. Marking field to focal plane parallelism, working (marking) height consistency, process flatness, and input beam alignment consistency all influenced the calibration, resultant accuracy, and marking consistency of the marking station. Unfortunately, these factors are not mutually exclusive, and their independent effects on the marking process are not easily differentiated, and often combine. As a result, each is specifically defined and its impacts on the marking process described below, in order to clarify their individual importance to the calibration and implementation of scanner units.

All effects of the error sensitivities discussed in this section vary in severity with the choice of F-Theta lens, focal length of the system, and field of view, but all can also be readily corrected through a mark-and-measure calibration procedure, as long as the aspects of the system's alignment which produce them remain constant. Therefore, the major concern regarding accurate and precise laser marking is the consistency of each spatial relationship discussed below. Deviation in any of the below alignments from the state in which the scanner was calibrated will invalidate the calibration of the marking system to some extent.

Marking Field & Focal Plane Parallelism

As used in this document, the "marking field" is defined as the planar surface on which the laser beam is intended to mark; it is bounded by the geometry of the part to be marked. Additionally, the "focal plane," as used herein, is defined as the virtual plane over which the optical elements

of the system focus the laser beam; it is bounded by the available scan area of the particular scan head/lens combination in use. The parallelism of these two planar surfaces is defined here as the magnitude of the angle between the normal vectors of each plane, and when referring to the effects of this parallelism, it is assumed that the centroid of each plane is coincident with one another and that both are perfectly flat. Through testing, the alignment of the two was found to have an impact on the marking accuracy, and therefore, the calibration of the scanner. As the input beam is directed through travel by the scan head, it inherently has an incident angle greater than zero as it falls on the focal plane (except for where the beam enters the lens coincident, and parallel to the lens' axis.) Any misalignment between the marking field and focal plane causes the beam to be projected a distance that is different than the intended working height, and, as a result of the non-zero incident angle at the focal plane, a mark placement error is induced on the marking field. The total (pk-pk) induced error over the marking field from a parallelism error is linearly dependent on the total scan length, and is non-linearly affected by the nominal incident angle of the laser beam on the part and the parallelism error between the marking field and focal plane. In instances where a non-telecentric focusing optic is used (non-zero nominal incident angles,) the peak-to-peak induced laser placement error can be on the order of microns per 100 micro-radians of parallelism error.

Marking Height Consistency & Process Flatness

Similar to errors caused by marking field and focal plane misalignment, errors can be induced when the marking field is placed at a different distance from the lens along its axis than the

theoretical location of the focal plane. This height differential can either be a result of a constant offset between the marking field and focal plane caused by a lack of consistency in the parts vertical placement in the system or be a result of the parts flatness with respect to the focal plane or a combination of the two. Errors induced by this height variation are solely a result of non-zero incident angle of the laser beam at the focal plane. Therefore, the use of telecentric focusing optics effectively eliminates this error source; however, if non-telecentric optics are used, induced peak-to-peak laser placement error across the scan length can easily be on the order of microns per five microns of marking field height variation. This placement error is linearly affected by variation in marking field height, and is dependent on the beam's incident angle at a given position within the focal plane.

Laser Alignment Consistency (Zero Offset)

The final error sensitivity of major concern when calibrating laser scanners is that associated with laser alignment. The largest part of the laser placement error to be corrected in scanner systems is injected from the focusing optic's distortion of the focal plane's coordinate frame produced from field flattening. The exact manner in which this distortion is manifested over the focal plane depends on the boundaries of the laser beam's entrance into the lens. The lens' distortion of the beam's projected position on the focal plane is a function of the incoming beam's distance from the axial center of the rear lens objective. The center point of the focal plane, or "zero" location of commanded moves, ideally corresponds with the laser beam passing coincident and parallel to the lens' axis. In this ideal condition, the theoretical lens distortion of the focal plane has two axes of symmetry, which coincide with the (X) and (Y) axes of the focal plane, as defined by the scanners' motion.

Realistically, the beam incoming to the scanner is never perfectly aligned, and as a result, the laser beam being projected to the commanded center point of the focal plane is linearly offset from the axial center of the lens as it enters the rear objective. This is what's referred to herein as a "zero offset." Due to this zero offset, the actual lens distortion imparted on the focal plane is asymmetrical.

Any change in either the linear or angular alignment of the input beam to the scan head will induce significant laser placement errors, in this case, at the focal plane itself (independent of the previously mentioned error sensitivities.)

The level of this induced error is significantly more sensitive to angular changes in the alignment of the input beam. Angular changes in the input beam are projected through the scan head over a long enough distance that even a small change can create a substantial change in zero offset at the lens' rear objective.

The manner in which a change in the zero offset of a scanner system induces error is through the shift between the location of the lens and the incoming laser beam, and the associated shift in the focal plane's distortion. For example, when applying a correction table via a calibration file, each value in the correction table is associated with a commanded position in the focal plane. However, the magnitude of each value is associated with where the laser beam passes through the lens relative to its axis when at its associated command position. Therefore, when a change in zero offset occurs, there is a relative shift between the commanded locations in the focal plane, and the location of the laser beam with respect to the lens. This shift destroys the validity of the connection between the magnitude of a correction in the table and the location it's associated with. As depicted in Figure 2, a zero offset shift from (X0, Y0) to (X'0, Y'0) changes every position of the laser beam throughout the focal plane the same amount relative to the lens' axis, thereby changing the magnitude by which the lens distorts each commanded position's global location on the focal plane. This relative shift between the focal plane and the lens' distortion map is depicted by the shift in (X1, Y1) to (X'1, Y'1) and (X2, Y2) to (X'2, Y'2). As a result of this shift, the correction counts intended to correct the lens' distortion at (X1, Y1) over correct for the distortion that exists at (X'1, Y'1) because it is now closer to the lens' axis and is distorted a lesser amount. Likewise, the correction counts intended to correct the lens' distortion at (X2, Y2) are now not enough to fully correct the distortion seen by (X'2, Y'2) because it is farther from the lens' axis and is thereby further distorted. Therefore, the amount of error induced by a change in input beam alignment is dependent on the magnitude and type of the change, the size of the AGV unit in use, and the slope of the correction table being employed by the calibration file (which is primarily a factor of the F-Theta lens in use.)

Lastly, while the effects of even large zero offsets, when left unchanged, can be effectively calibrated, their impact on spot distortion cannot. A shift in zero offset also changes the distortion imparted focused laser spot.

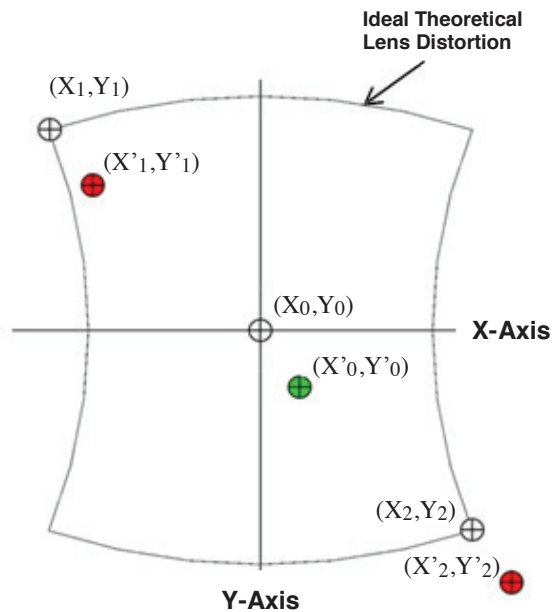


FIGURE 2. Depiction of a relative shift between commanded locations in the focal plane and a map of the ideal theoretical distortion created by an F-Theta field flattening lens, referred to as a change in zero offset.

Lens manufacturers offer theoretical software simulations of spot size deviation and focus quality as a function of position within the focal plane. As a result of non-ideal laser alignment, spot size deviation will be larger and patterned differently than what is predicted by the manufacturer. This can have a drastic effect on the quality of marks used for calibration as well as weld quality and stability related to where the laser spot is in the focal plane while performing a sintering operation.

SUBSTRATE VIABILITY & MARK QUALITY

As a result of good spatial control of the laser marking station studied, uncertainty in the measurement of calibration artifacts was found to be the primary limitation to the scanner's calibration. Measurement uncertainty and therefore the effectiveness of a calibration are dependent on the substrate as well as the quality of marks being made on that substrate when used in the mark-and-measure procedure outlined above. As previously mentioned, the calibration in the study employed the use of a machine vision system. As such, the level to which the mark-and-measure procedure was able to calibrate a scan head was directly affected by the camera's ability to accurately measure each mark in the grid patterns created. The marked substrate needed to produce a high level of contrast in the camera image; it needed to have exceptional surface finish to provide a solid background; lastly, the marks needed to be

thin and had to have crisp edges in order to produce the highly repeatable marking and measuring necessary for high accuracy calibration.

Measurement Repeatability & Marking Repeatability

Two major limiting factors in scanner calibration are the consistency with which the camera determines the center of a given mark, and the consistency with which the laser makes marks on the substrate. The nomenclature coined to represent these two factors is "measurement repeatability" and "marking repeatability." Measurement repeatability is defined herein as the maximum peak-to-peak difference in the measurement of a single mark's center between subsequent measurements of the same grid of marks. Conversely, marking repeatability is defined as the maximum peak-to-peak difference in the measurement of subsequently marked grids, assuming an identical setup and marking field to focal plane relationship. As such, marking repeatability can never be exclusively determined because it is inherently inclusive of measurement repeatability and the effects of the aforementioned error sensitivities. It must be estimated. An illustration of measurement and marking repeatability is provided in Figure 3. Combined, the measurement repeatability and marking repeatability establish the effective resolution of the calibration, and, therefore, must be minimized to obtain high levels of marking accuracy.

Making High Quality Laser Marks

Through the case study, it was found that thin marks produce the best results in both measurement and marking repeatability. Thinner marks produce better results because they fundamentally do the least amount of damage to the substrate, and thereby impart the least amount of heat into the substrate. This causes very thin marks to have minimal heat affected areas and insignificant mark growth relative to the theoretical focused spot size. Mark growth due to excess heat and/or a large heat affected area are major causes of mark randomness in addition to the substrate surface consistency. Minimizing excess heat input is the key to increasing the repeatability of a mark's shape (marking repeatability.)

Also, minimizing damage and heat input makes the contrast transition band between marked area and background very narrow in the camera image. The abrupt contrast change is what is described here as "crisp" marking. Having very crisp marks provides fewer inputs to the

camera's edge search algorithms, reducing the total number of influences on its opinion of a mark's center. Limiting the amount of pixels involved in the camera's search algorithm, therefore, gives it fewer items to change its opinion over, and showed to improve measurement repeatability substantially.

The ability to make the small, crisp, high quality marks described above is dependent on two factors, substrate selection and the laser parameters used for marking. Both are important to achieving high quality marks, but the ideal laser marking parameters for making a high quality mark can differ from substrate to substrate, making them difficult to specifically define.

As mentioned above, high accuracy calibration using machine vision requires that the substrate have superb surface finish, produce crisp marks with good contrast, and be strictly dimensionally controlled. As such, it was found that glass substrates with optical quality thin film coatings made good substrate candidates. However, using a coated substrate required certain considerations in the selection of laser parameters. When a laser has to burn through any thickness of coating to make a mark readable, it will impart more energy to the surface layer than is required to do damage as the beam passes through the coating's thickness. This naturally causes an increase in heat affected area and mark growth at the surface layer, which, in this case, was the camera's image plane. Not only is the mark,

therefore, inherently bigger in the image plane than the laser spot, but also it inherits randomness in its size, edge, and overall shape. All three reduce overall calibration resolution (marking & measuring repeatability.) It is imperative to impart as little thermal energy as possible to the area of surface layer surrounding the laser spot while fully burning or ablating the area underneath the spot to achieve quality marks. These thermal effects, mark growth and heat affected area, are not unique to marks made on coated substrates; they are only magnified by the coating. High accuracy mark-and-measure calibration demands that these effects be minimized regardless of the materials and processes used for marking. This minimization is achieved through the selection of the laser marking parameters.

Typically, the operator of a laser marking system has control of certain explicit laser marking parameters, such as average output power or pulse energy, pulse width or modulation frequency, marking speed, etc. However, it is the implicit marking parameters that determine the overall quality of a mark, specifically average power density, pulse power density, and average power seen by the substrate. The key to making quality marks that approach the theoretical laser spot size without producing the undesired thermal effects is to achieve high average and pulse power densities while reducing the average power dumped into the substrate. Examples of poor and high quality laser marks are shown below in Figure 3.

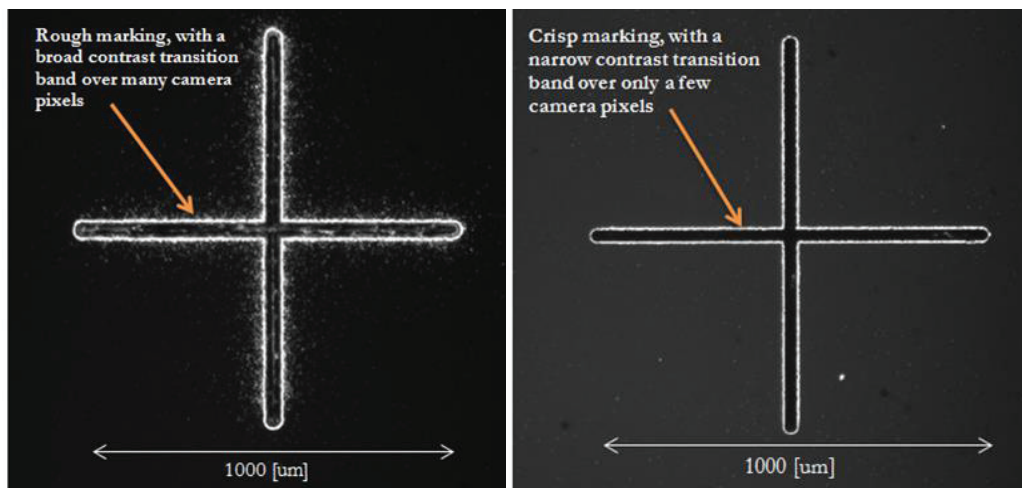


FIGURE 3. Examples of a poor quality mark (left) and a high quality mark (right) for potential use in the calibration of a scanner unit. The ~1 [mm] long crosshair marks were made using Aerotech Inc.'s AGV-14HP-1064-100T configured scanner. The marks were made on a metallic thin film coated glass substrate with a YAG fiber laser operating in pulsed mode. The high quality mark's inner width is ~40 [μm], nearly the size of the theoretical focused $1/e^2$ Gaussian laser spot diameter.

CALIBRATION RESULTS & CONCLUSIONS

Below are the documented results of the fore mentioned case study on mark-and-measure calibration. The purpose of the study was to determine and document the readily achievable marking accuracy of an Aerotech AGV-14HP-1064-100T scanner system when calibrated using Aerotech's High Precision Inspection Station via the mark-and-measure technique.

The study was not meant to define the absolute limit for marking accuracy in scanner based systems, nor was it directly a representation of the rotational accuracy of scanners within Aerotech's AGV-14HP model scan heads. The experiment was meant only to act as an example of the output accuracy that a similarly fitted laser processing system might be able to attain when attention is given to the principles and considerations discussed above.

Results

After mark-and-measure calibration, the AGV-14HP-1064-100T scanner unit achieved 2D marking accuracies on the order of singular micrometers of error. The total calibration took two calibration iterations (three marked grids) to return no improvement in accuracy. Table 1 shows a summary of the measurements taken from the final grid marked by the scanner. It is important to note that the achieved accuracy is roughly equal to the approximate measurement uncertainty of the grid. Thus, the achieved accuracy has reached the effective calibration resolution for this particular system.

Conclusions

In this case study, an AGV-14HP-1064-100T galvanometer scanner was calibrated using a

mark-and-measure methodology to give insight into the levels of marking accuracy achievable with this type of calibration approach. It was learned that the effectiveness of a mark-and-measure calibration procedure is largely dependent on the combination of substrate and laser parameters used for marking. The combination of these two factors determines the overall mark quality of the fiducials made in terms of measurability and measurement repeatability. The mark quality, in this study, was the majority contributor to measurement uncertainty, and therefore was the limiting factor in the calibration outcome.

For marking accuracy to be limited by the repeatability of the galvanometer motors themselves along with the impacts of one's ability to control the spatial relations of the marking station, measurement uncertainty must be minimized. Regardless, the achievable accuracy of the laser marking system will be the combination of the galvanometer motor's repeatability, the effects of spatial non-repeatabilities in the system setup, and the uncertainty in the measurement process. Therefore, this summation should be at or lower than the accuracy goals of the process at hand, in this instance DMLS.

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Note: This paper is a direct modification of reference [1] with practically no addition of new material. It is merely a resubmission of [1] with a reduction of its size and scope.

TABLE 1. Measurement summary of the final grid made during the Mark-and-Measure calibration of an AGV-14HP-1064-100T scanner unit.

Summary of Achieved 2D Marking Accuracy			
Metallic Coated Glass Substrates			
Calibrated Field Size = 40 x 40 [mm]			
Camera Resolution = 0.86 [$\mu\text{m}/\text{pixel}$]			
Scanner:			AGV-14HP-1064-100T
Measurement Uncertainty [$\mu\text{m pk-pk}$]:			2.50
X-Axis	X Marking Accuracy [$\mu\text{m pk-pk}$]:		2.65
	X Avg. Linearity [%]:		99.997
Y-Axis	Y Marking Accuracy [$\mu\text{m pk-pk}$]:		2.33
	Y Avg. Linearity [%]:		99.998
X-Y Orthogonality [arc-sec]:			0.01
Vector Sum Error [$\mu\text{m pk-pk}$]:			1.40

MULTI-SCALE EVALUATIONS OF THE ROUGHNESS OF SURFACES MADE BY ADDITIVE MANUFACTURING

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INTRODUCTION

This work evaluates the measured topographies on surfaces made by an additive manufacturing (AM) process for polymers. Multi-scale analyses scales of length, area and their scale derivatives are used to find crossover scales where there are changes in the nature of the topography. In all manufacturing processes there are limits to the surface topographies that can be produced. These limits can be represented in part by the crossover scales. Understanding these scales is important for selecting process variables in AM and for designing tooling for AM that can improve the control of the surface texture.

At sufficiently large scales manufactured surfaces can appear to be smooth. At sufficiently fine scales they appear to be rough [1]. The scale at which this change takes place is called the smooth-rough crossover (SRC).

Surfaces created in additive manufacturing are similar in some respects to some other kinds of manufactured surfaces. Larger components of the topography can be sensitive to the process variables. Finer components of the topography can depend on fine-scale tool-material interactions. What is commonly called roughness can have larger scale features that have a high degree of regularity that are dependent on the layer thickness. At finer scales there are features that have a high degree of irregularity which are formed by the material deposition process, flow and curing. The topographies at finer scales are more complex than those at the finer scales.

No previous studies on AM surfaces, of which the authors are aware, have focused on determining crossover scales using multi-scale analysis [e.g., 2, 3]. Multi-scale analysis is used to decompose the manufactured topographies to

study the periodicity and crossover scales between periodic and aperiodic components of the topographies. The topographies are compared statistically at scales below the periodic components.

METHODS

A Dimension SST 1200ES Fused Deposition Rapid Prototyping Machine was used to make 10mm cubes with one edge beveled at an angle of 45 degrees as shown in Fig. 1. Layer thicknesses of 250 μ m and 330 μ m were used. In this fused deposition method parts are created layer by layer from a thermoplastic extrusion in semi-liquid state of ABS two different layer thicknesses were studied. The outer boundary of each layer, which becomes the surface of the part, is deposited then the inside is filled.

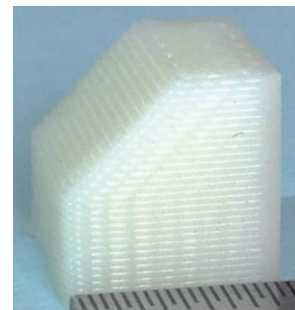


FIGURE 1. Macrograph of the part 10mm cube with an angled bevel made with 330 μ m layers.

Surface measurements on the sides, angled bevel face and top edge were made with an Olympus LEXT OLS4000 confocal microscope with the 100x lens. Individual measurements were stitched to cover extended regions. The individual region measurement size is 121x121 μ m, consisting of 1024x1024 elevations with an initial sampling interval of 227nm. This

initial sampling interval is modified apparently during the subsequent stitching operation.

A slope filter was used in Mountains®7 software (Digital Surf) to remove numerous aberrant heights, or spikes, which are apparently measurement artifacts in low brightness regions. The spikes were especially prevalent in the narrow regions between the layers. This slope filter removes portions of the measurement where slopes that are steeper than some threshold selected by the user, in this case 87.5 degrees. This method removes unlikely height measurements without altering the rest of the measurement. The heights where the spikes were removed were replaced using the surrounding average heights. This results in some smoothing of the measurement where the spikes have been replaced. The supposition is that, despite the smoothing, this process makes the measurement more useful by eliminating unrealistic artifacts which would markedly increase the relative lengths and areas.

Measured regions were selected to avoid obvious, large defects, which were cropped from the larger stitched regions and then leveled. This was done with Mountains®7, which was also used to render the measurements into images (Fig. 2).

Multi-scale evaluations of the relative lengths of the profiles, and relative areas of surfaces [4], using Sfrax (Surfract.com), were performed on profiles and surface sections perpendicular to the deposited layers. These selected regions include cross sections of three of the deposited layers (Fig. 2).

Length-scale analysis uses line segments in repeated tiling exercises at different scales to determine profile lengths as a function of scale [4]. The length of the line segment represents the scale and remains constant in each individual tiling exercise. Relative lengths are determined at each scale from the ratio of the measured length of the profile to its nominal, or straight-line, length. The relative lengths are calculated over a range of scales from the profile length to the sampling intervals.

Multi-scale evaluation of the relative areas, i.e., area-scale analyses [4,5] were performed on selected crests where the layer bulges. Area-scale analyses are similar to length-scale analyses. Relative areas are determined, rather

than relative lengths. Triangles are used, rather than line segments, to tile areal measurements ($z=z(x,y)$), rather than profiles ($z=z(x)$).

The complexities are the scale-based derivatives determined over decade intervals of the relative lengths or areas. The complexity indicates how the relative lengths or areas change when the scale changes.

Multi-scale discrimination testing is performed on relative areas and their complexities at all the scales in selected regions. The relative areas and their complexities are calculated from a portion of the measurement (192x192 μ m) of the highest region on one of the deposited layers, as indicated in Fig. 2. Form was removed with a second order filter in Mountains7. These regions were split into four sections (2x2) in Sfrax to allow statistical comparisons between the surfaces. An F-test is used to determine the mean square ratio (MSR) which is compared with critical values for determining the level of confidence for discriminating the surfaces based on their relative areas at each of the available scales. The MSR is plotted versus the scale.

RESULTS

Renderings of selected portions of surfaces measured from the side and angled bevel of the cube with a layer thickness of 254 μ m are shown in Fig. 2. Full measurements are shown in the Appendix. A regular pattern corresponding to the layer thickness is evident in Fig. 2. The layer thickness is readily detectable from the images. Note that the topographies in the valley regions between the layers have been smoothed by the height replacements after spike filtering.

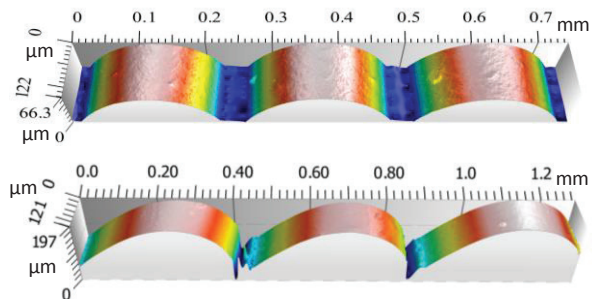


FIGURE 2. Rendering of surface measurements from side (above) and angled bevel (below) with 254 μ m layers.

The values of conventional parameters for the four surfaces are shown in Table 1.

parameter→	height (μm)				hybrid	
surface↓	Sa	St	Sq	Sp	Sdq	Sdr %
254 side	18.3	66	20.9	25.9	0.83	21.9
330 side	24.3	139	28.2	39.3	4.29	51.2
254 angled	37.1	159	43.5	49.7	2.22	58.4
330 angled	40.1	197	48.2	56.9	2.28	48.4

TABLE 1. ISO 25178 height and hybrid parameters [5].

Plots of the relative lengths versus scale are shown in Fig. 3 for profiles in the longitudinal direction, i.e., perpendicular to the layers, from the side and angled bevel surfaces shown in Fig. 2. Three different regions of scale can be delineated by multi-scale consideration of the relative lengths. At the large scales, above about $250\mu\text{m}$ and $350\mu\text{m}$, for the side and angled surfaces respectively, the relative lengths vary regularly and remain close to one. Between these larger scales and a scale of about $30\mu\text{m}$ for both surfaces, there is a transition region where the relative lengths tend to increase markedly and irregularly. At scales below about $30\mu\text{m}$ the relative lengths continue to increase, although at a lower rate with respect to decreasing scale, until the sampling intervals, 300 to 400nm , are reached.

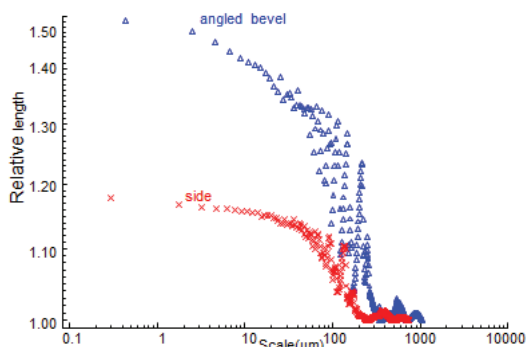


FIGURE 3. Relative lengths v. scales for side and angled bevel surfaces with $254\mu\text{m}$ layers.

Details of the two crossovers between the three regions for relative length are shown in Fig. 4. At the largest scales the relative lengths increase slightly, and then return to values close to one again. This happens two times before increasing definitively to larger values at all the finer scales. The finest scale at which the relative length approaches one, before increasing definitively at

the finer scales, can be designated as a kind of SRC [1,4,6]. SRC values are plotted in Fig 5. At the intermediate scales the relative lengths irregularity appears to be quasi-periodic, in a series of waves.

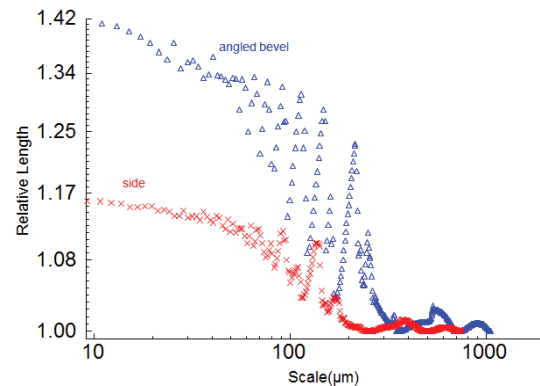


FIGURE 4. Larger scale details of the relative lengths v. scales for side and angled bevel surfaces with $254\mu\text{m}$ layers.

The SRC can be seen to increase linearly with the modified layer thickness (Fig. 5). In Fig. 5 the layer thickness on the angled surfaces is modified by multiplying by the square root of two ($1/\sin(45^\circ)$), which is intended to account for the angle of the bevel. With this accounting for the angle of the bevel, the layer thickness and the SRC are shown to be strongly correlated. The regression coefficient (R^2) is greater than 0.99, the slope is about 0.9 and the intercept is less than ten percent of the mean value of the SRCs. The height parameters in Table 1 would all increase monotonically, as well, when plotted as in Fig. 5. This similarity in trends with the SRC is consistent with the premise that these height parameters are most sensitive to some of the larger scales in the measurements, like the SRC. The hybrid parameters are most sensitive to the finest scales, and do not show similar increases with the modified layer thicknesses.

The length-scale complexities are compared between the side and the bevel for all the available scales shown in Fig. 6 for the $254\mu\text{m}$ and $330\mu\text{m}$ layers respectively. In both cases the angled surfaces tend to have greater complexities than the sides. There is a marked decrease in the complexity in all cases at the finer scales. There is no consistent evidence, however, of any tendency towards a common complexity at the finest scales.

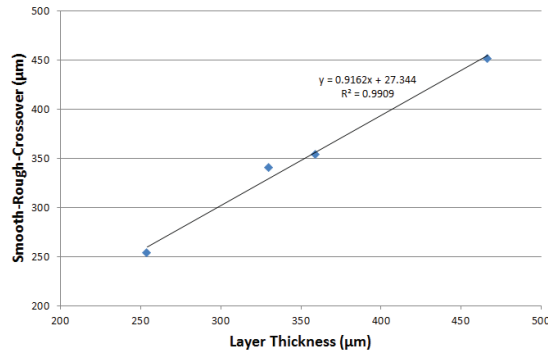


FIGURE 5. Smooth-rough crossovers v. layer thickness and modified thickness for the bevels.

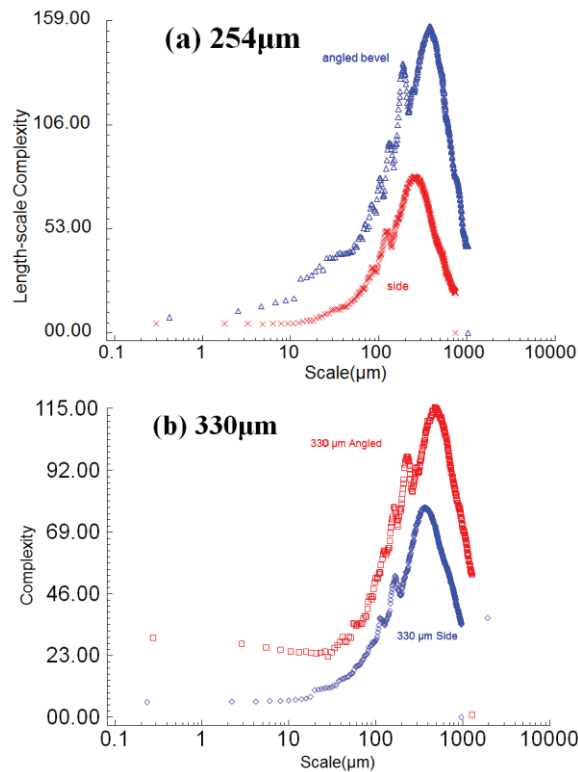


FIGURE 6. Length-scale complexity v scale for the (a) 254μm above and (b) 330μm below.

Rendering of surfaces used for the area-scale analyses, taken from crests of the layer bulges are shown in Fig. 7. The relative areas, results of the areal multi-scale analyses from the selected crest regions, are shown, versus areal scales in Figure 8. The largest linear scale in these analyses is about 30μm, well below the SRC for relative lengths. The linear scale is half the square root of the triangular areal scale. For all surfaces, with the form removed, the relative areas tend toward one at the largest scales. In these regions, formed removed, the SRCs are

about 100μm² or 5μm. There appears to be no relation between relative areas and the large-scale processes, i.e., layer thickness and bevel.

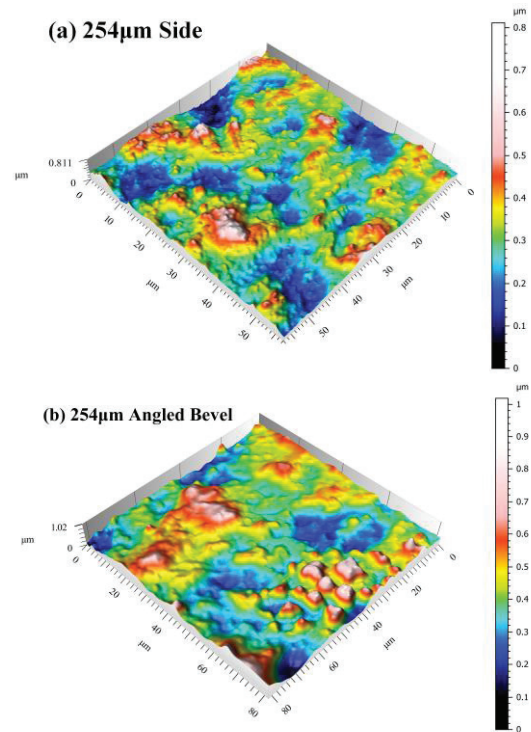


FIGURE 7. Extracted region with form removed from 254μm crests (a) side and (b) angled bevel.

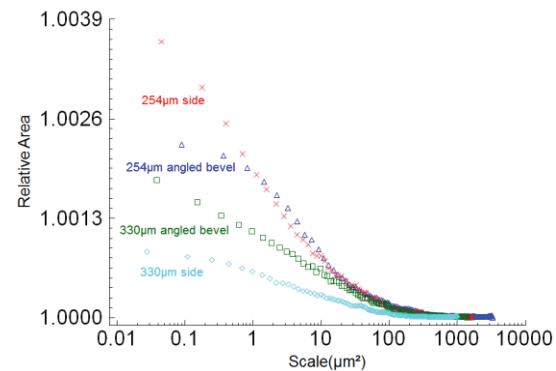


FIGURE 8. Relative areas v scale from the selected crests from the all the surfaces.

Area-scale complexities are shown versus scale in Fig. 9 for the selected regions. All the surfaces have maximum complexities between 0.4 and 20μm².

The results of multi-scale discrimination testing using F-tests on the complexities at each scale are shown in Figures 10a and b. The mean square ratio (MSR) is plotted versus scale, and

the critical MSR for 99.9% is indicated. In both comparisons, as indicated by the MSR, the ability to discriminate is consistently strong below scales of about $20\mu\text{m}^2$, strongest at about $10\mu\text{m}^2$ then diminishes at the finer scales. The ability to discriminate the sides (Fig. 10a) is greater than it is for the angled bevel surfaces (Fig. 10b) as indicated by the MSR values.

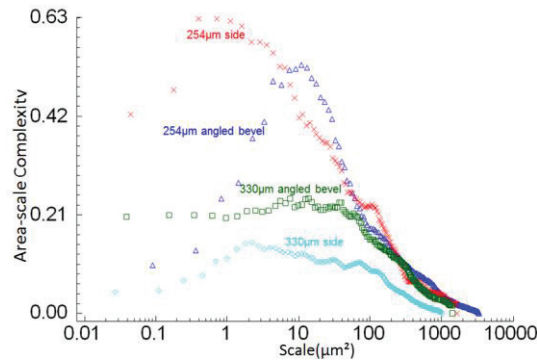


FIGURE 9. Area-scale complexity v scale from selected crests from the all the surfaces.

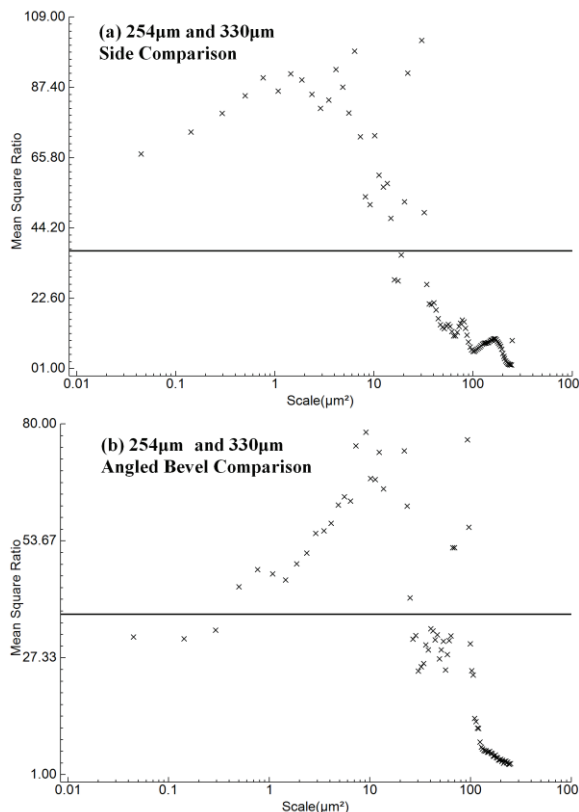


FIGURE 10. Multi-scale discrimination from area-scale complexity v scale from selected crests from (a) sides and (b) bevels of 254 and $330\mu\text{m}$ layers.

DISCUSSION

Multi-scale analysis of the roughness of fused deposition parts is effective at identifying different natures of the topographies at different scales. At scales of and above the layer thickness there is a strong relation with relative minimums in length-scale analyses. At scales just below the layer thickness there is a high degree of complexity in the surface topography. At the finest scales the study, from some hundreds of nanometers to some tens of micrometers the complexity of the surfaces is distinctly less complex than at scales from tens of micrometers to just below the layer thickness.

The topographies at the finest scales retain individuality with respect to the process variables. It is not clear why they should not be more similar. The finest scales are removed from the scale of the layer thickness by three orders of magnitude. It could be supposed that the formation of the roughness at these scales should be similar, regardless of the layer thickness. The hybrid parameters, which have been found to be similar to the relative areas at the finest scales [7] do not rank with the modified layer thickness.

The roughness could be reduced by reducing the layer thickness. The remaining roughness, shown in Fig. 7, is apparently due to other aspects of the process, and might not be eliminated by reducing the layer thickness.

The strong correlations between layer thickness and SRC are similar to those that have been found with feed in turning and SRC [6]. There is also individuality of the topographies at scales below the feed in turning and below the layer thickness in fused deposition. In both cases, turning and fused deposition, the topography at the scales of what might be called the dominate process variable, feed per revolution and layer thickness, are regular. At finer scales the topographies become chaotic.

The quasi-periodic variation of the relative lengths at, and just above and below the scales of the layer thickness is due to the interaction of the tiling algorithm with the larger scale regularity of the layered topography. There is distinct aliasing at even multiples of the layer thickness. At those length scales the tiling algorithm is blind to the topographic variations. At scales just below the layer thickness the tiling

algorithm is interacting in quasi-regular intervals at the scales of different fractions of the layer thickness.

The lack of evidence of a correlation at the finer scales with the dominate process variables could be a function of the small sample size used here. If there were to be some correlation, then the layer thickness could be influencing the formation of the topography at the fine scales. This and the topographic formation mechanisms at the fine scales are beyond the scope of the current work.

The optical measurement of the fused deposition surfaces can present some issues. The deep valleys separating deposition layers can be difficult to get what appear to be realistic height measurements from. The surfaces studied here have been subjected to slope filtering and replacement.

The observation that the layer thickness divided by the sine of the angle of the bevel correlates strongly with the SRC is evidence that the deposition bead has an elongated, rounded-rectangular cross section.

CONCLUSIONS

1. Multi-scale analyses using length-scale and area-scale tilings are able to distinguish regions in scale with distinctly different natures.
2. The relative lengths at scales comparable to the layer thickness and greater show a high degree of regularity. The period depends on the layer thickness and surface orientation.
 - 2.1. The layer thickness appears to be closely related to the scale of the smooth-rough crossover on the length-scale plot.
 - 2.2. The smooth-rough crossover calculated from measurements of the angled bevel region is close to the layer thickness times the sine of forty-five degrees.
3. The area-scale complexities of crests of the layer bulges differ significantly between the parts at scales below about $20 \mu\text{m}^2$.

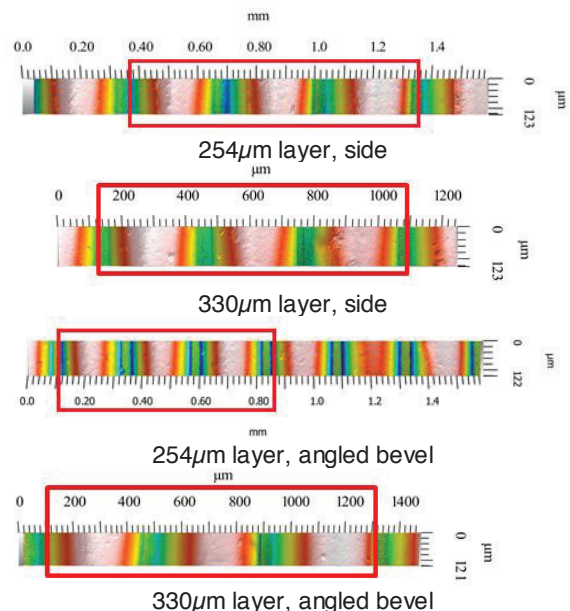
ACKNOWLEDGEMENTS

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APPENDIX



FUNDAMENTAL STUDY ON THE WORLD'S THINNEST LAYERED MICRO-STEREOLITHOGRAPHY USING EVANESCENT LIGHT

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INTRODUCTION

Microstereolithography is recognized as one of the most important micromanufacturing techniques available today [1]. Especially, with the increasing demand for micro 3D structures manufacturing with a spatial process resolution of submicrometer in various fields such as micro-electro-mechanical, micro-opto-mechanical, and microfluidic systems, and so on, the highest degree of flexibility in micro 3D fabrication of microstereolithography is rapidly gaining in importance [2]. A number of microstereolithography techniques [3, 4] have been developed, which can be classified into two main types on the basis of the principle employed: two-photon photopolymerization [5] and layer-by-layer microstereolithography [6, 7] (Table 1).

In this research, by taking advantage of its practical higher productivity of one-shot layer-by-layer microstereolithography [6] (Fig. 1), we propose a method using not only conventional propagating light but also using near-field evanescent light, which allows us to localize the light energy for photopolymerization to a thin layer with a thickness of submicrometer scale [8, 9].

As the first step to realizing the proposed method, in this report, we present a theoretical analysis of cured layer thickness characteristics of an evanescent light exposure. Furthermore, we confirm the feasibility of lamination process of cured layer using evanescent light.

MICRO-STEREOLITHOGRAPHY USING EVANESCENT LIGHT

The concept of the proposed microstereolithography in a layer-based production fashion using evanescent light is shown in Fig. 2 in contrast to the conventional

propagating light exposure. Here, instead of a glass plate at the bottom for a fixed surface exposure, a solid immersion lens (SIL) is used as both a high-power imaging tool and a high-refractive-index material for total internal reflection (TIR). Under this condition, evanescent light exposure can be performed when light with an incident angle smaller than the critical angle is blocked from reaching the surface.

For vertical resolution characteristics in the case of the propagating light exposure, its minimum fabricatable layer thickness depends largely on the penetration depth of the light absorption of the photosensitive resin. Since the controllability of absorption property of photosensitive resin is limited, it is difficult to achieve a submicrometer

TABLE 1. Characteristics of microstereolithography [9].

	Two-photon polymerization	Layer-by-layer microstereolithography	
Spatial process resolution	Submicrometer (100 nm scale) Less than diffraction limit is possible because of multi-photon absorption.	Lateral	About 1 μm [Due to diffraction limit of relatively longer working distance of projecting lens]
		Vertical	About 5 μm [Due to surplus growth of propagating exposure light]
Process time	Low [Point scanning exposure]	High [Simultaneous surface exposure, especially in one-shot type]	

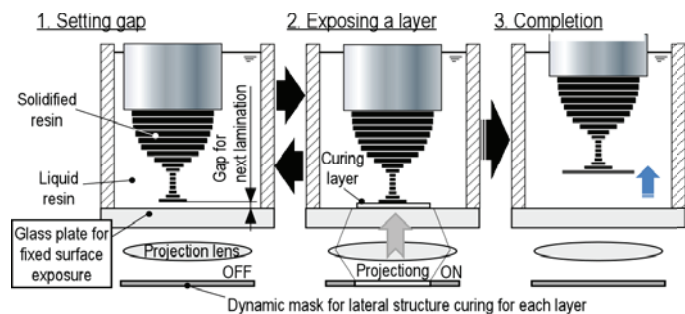


FIGURE 1. One-shot layer-by-layer microstereolithography [9].

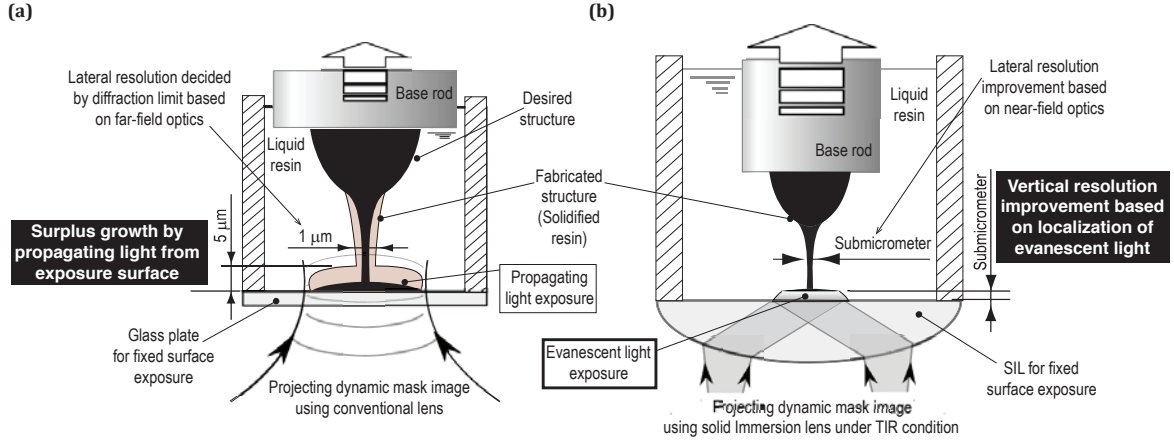


FIGURE 2. One-shot layer-by-layer microstereolithography using propagating light (a) and evanescent light (b) [9].

thickness. Furthermore, the conventional propagating light can easily cause surplus growth of over 1 μm , especially around overhanging features, because some of the light travels through the cured resin layer, as shown on the left in Fig. 2. In contrast, with the proposed method, the penetration depth can be expected to strongly depend on the vertical localization of the evanescent light itself rather than the absorption characteristics of the photosensitive resin. This is why a submicrometer layer thickness resolution can be expected.

THEORETICAL ANALYSIS OF THICKNESS OF EVANESCENT LIGHT EXPOSING LAYER

Based on the Lambert-Beer law, and the Maxwell's equations, the curing layer thickness of the proposed method, C_d , can be described using the critical exposure energy of the resin U_c as follows:

$$C_d = \frac{\lambda_0}{\alpha \lambda_0 + 4\pi n_2 \sqrt{(n_1/n_2)^2 \sin^2 \theta - 1}} \ln \frac{\tau(\theta) U_o}{U_c}, \quad (1)$$

where, $\tau(\theta)$, U_o , θ , α , λ_0 , n_1 , and n_2 denote a proportionality factor independent of the depth z [10], the energy of the incident light, the incident angle of the exposure light, the absorption efficient of the photosensitive resin, the wavelength of the incident light for exposure, and the refractive index of the SIL and photosensitive resin, respectively.

Fig. 3 shows a plot of the curing layer thickness against the exposure energy of evanescent light from equation (1) under the following typical curing conditions: $\tau(\theta) = 2.52$ [10] (meaning p-

polarization state), $n_1 = 1.78$, $n_2 = 1.51$, $\theta = 68^\circ$, $U_c = 100 \text{ mJ/cm}^2$, $\lambda_0 = 488 \text{ nm}$, and $\alpha = 100 \text{ cm}^{-1}$. For comparison, the curing layer thickness with conventionally propagating light is also shown for the same conditions (but $\theta = 45^\circ$). From the figure, we see that the same incident light energy used in the conventional method can be employed for evanescent light photopolymerization. For example, at 3000 mJ/cm^2 , the conventional method photopolymerizes a layer thickness over $100 \mu\text{m}$, whereas evanescent light exposure photopolymerizes a thickness of under $1 \mu\text{m}$. Fig. 4 shows an apparatus of evanescent light exposure experiment for confirming submicrometer scale cured layer thickness, which was presumed in the theoretical analysis. An exposure result under total internal reflection ($\theta = 68^\circ$) suggests that submicrometer layer thickness resolution in the vertical direction can be achieved as shown in Fig. 5.

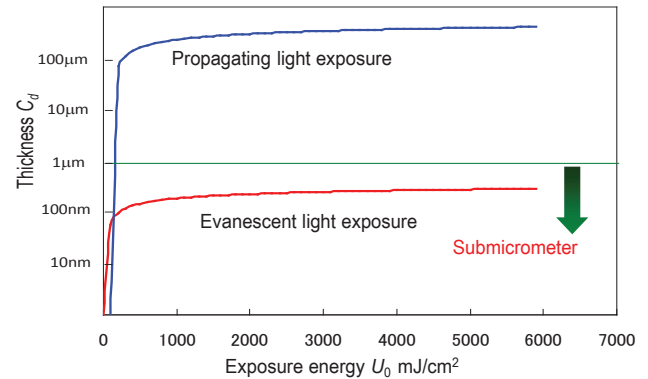


FIGURE 3. Theoretically calculated cured layer thickness C_d against exposure energy U_0 .

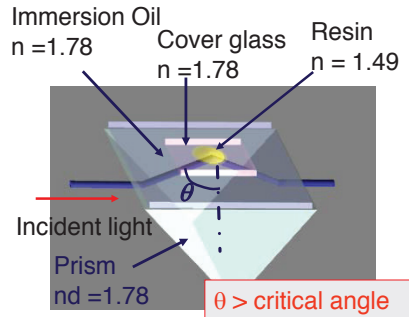


FIGURE 4. Evanescent light exposure experiment using prism (Photosensitive resin: KC1042, JSR).

VERIFICATION EXPERIMENT LAMINATING THIN LAYER CURED BY EVANESCENT LIGHT

We developed the experimental system shown in Fig. 6 to investigate whether the proposed method could be used to laminate a previously cured layer as a demonstration of layer-by-layer microfabrication [11]. This system consists mainly of an image source unit, a filter unit, an exposure unit, a lamination unit. A light emitting diode providing visible at 470 nm as a light source was installed at the image source unit. This unit provides us the method to control lateral light distribution by using this DMD masks. A low pass filter at the position of a Fourier transform plane of the DMD plane allows an evanescent light exposure on a photosensitive resin located on a cover glass, which is set with the objective lens under the total internal

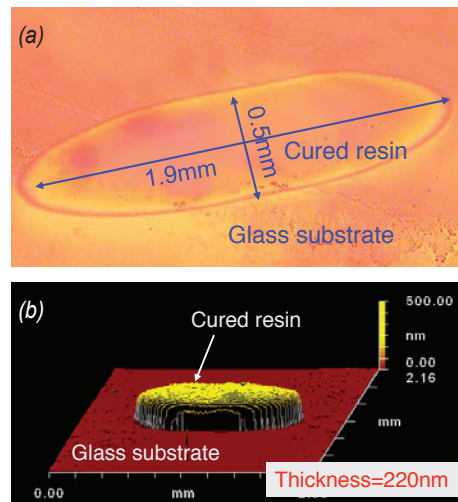


FIGURE 5. Result of evanescent light exposure experiment using prism. (a)Optical microscopic image, (b)Thickness measurement with white light interferometer.

reflection condition. We employed the lamination unit with a nano meter resolution linear stage and base rod. We employed TMP-A (light acrylate) and Irgacure 784 (photoinitiator) as photosensitive resin. The refractive index of this photosensitive resin is 1.5. Fig. 7 shows a fundamental laminating experiment. In this experiment, after curing the pillar by propagating light, we tried to laminate a thin layer cured by evanescent light. From a SEM observation, even an evanescent light exposing layer can be laminated on a previously cured layer.

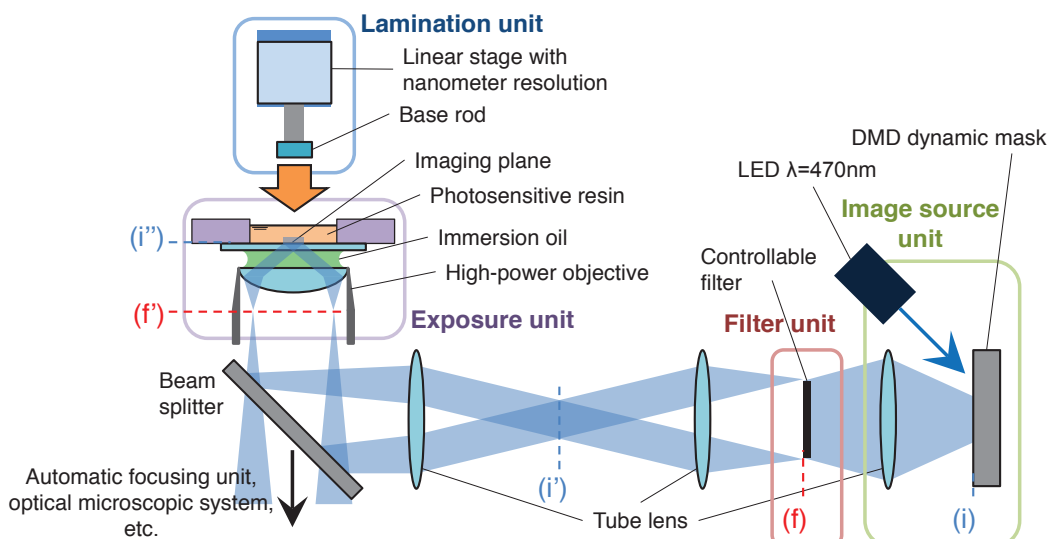


FIGURE 6. Experiment system for laminating evanescent light exposing layer [11].

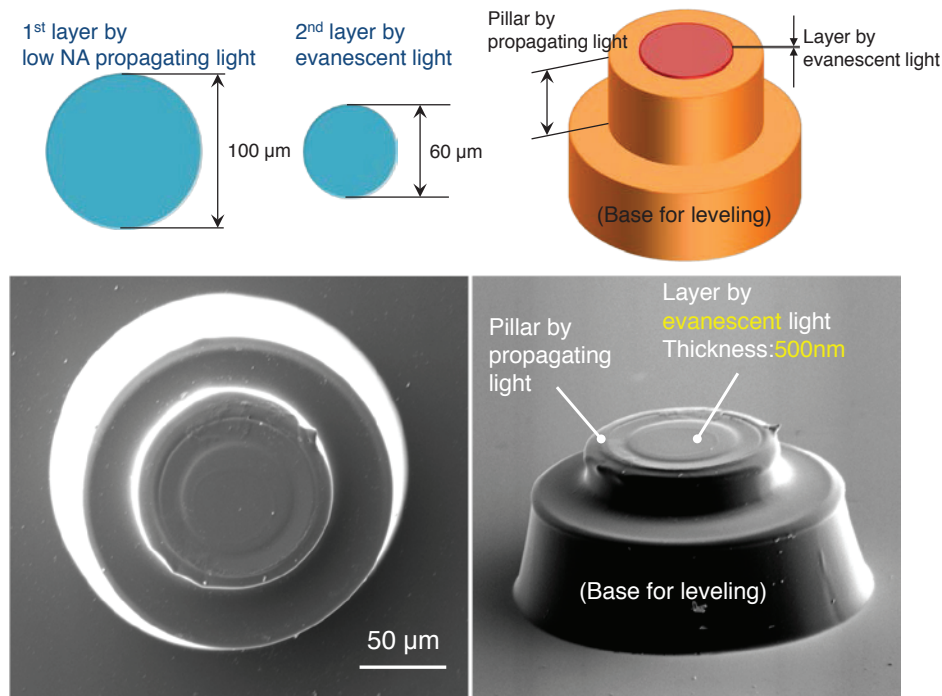


FIGURE 7. Fundamental experiment confirming lamination of evanescent light exposing layer.

CONCLUSIONS

We proposed the use of the spatially localized evanescent light instead of conventional freely propagating light in one-shot layer-by-layer stereolithography to achieve submicrometer spatial process resolution. Both theoretical and experimental analyses suggest that the proposed method allows us to fabricate submicrometer thin layer for one-shot layer-by-layer microstereolithography.

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A NOVEL TEST ARTIFACT FOR PERFORMANCE EVALUATION OF ADDITIVE MANUFACTURING PROCESSES

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INTRODUCTION

Additive Manufacturing (AM) has become widespread in recent years for rapid prototyping due to its aptitude to create functional parts with complicated three-dimensional (3D) geometries that are difficult or impossible to fabricate through subtractive manufacturing techniques [1-2]. Additive Manufacturing (AM), or layer-by-layer manufacturing, refers to a process of creating a 3D object from a digital model [3]. Due to its unique advantages such as the highest possible degree of design freedom and rapid design-to-fabrication turnaround, AM has received more attention recently.

Several AM technologies have been developed to attain unprecedented level of complexity for functional parts in a myriad of engineering applications. Current AM techniques include selective laser sintering (SLS), laminated object manufacturing (LOM), fused deposition modeling (FDM), and photo-polymerization [1-2]. Each AM technology possesses its unique physical mechanisms enabling joining materials to form 3D parts. These mechanisms determine the distinct characteristics of the process. Unlike conventional manufacturing techniques, which rely on removal of material by methods such as machining and laser cutting, AM processes create complex geometries by selectively adding successive layers of material with prescribed resolution [1-4].

Having relatively high production time and high material cost, current AM techniques cannot be adopted for high volume production purposes [2-3]. Yet, AM processes have played a key role in rapid-prototyping, and latterly, in fabrication of complex geometry, low volume, high-value parts such as bionic structures and the parts used in the aerospace industry. Hence, the output quality of the parts fabricated by AM processes is crucial to effective decision making during product development and to performance of high-value complex components. Therefore, it is paramount to assess the quality characteristics

of the parts fabricated by AM processes. These assessments must lead to better understanding and prediction of process outcomes [5].

Geometric accuracy and repeatability of AM processes are two significant output quality characteristics that can be used for performance evaluation [5]. For commercial AM processes, an indirect evaluation is performed by assessing the geometric characteristics of fabricated parts rather than direct measurements of machine motions [5-6]. Indeed, the indirect evaluation of the process is very relevant since it incorporates the effect of all different machine and process characteristics that contribute to the quality of the final product [7].

A broadly accepted approach for performance evaluation of AM processes is to fabricate a specifically designed test artifact that enables the assessment of output quality. To this end, Juster *et al.* [8] proposed a test artifact design with several basic features such as bosses, cylindrical holes, thin walls, cylindrical columns, and two free-form features. However, the designed features were not capable of testing 3D accuracy and repeatability. Byun *et al.* [9] proposed another test artifact with more features to address the drawback of unused substrate space. However, this artifact also failed to facilitate the repeatability assessment due to the lack of multiple identical features. More recently, Dimitrov *et al.* [10] proposed a test artifact that enables the investigation of process accuracy in three dimensions. Although many identical features were included in this design for repeatability testing, there were still some challenges to obtain repeatable measurements due to the complexity of features. Furthermore, the proposed design was not capable of demonstrating the limitations of AM processes due to the lack of similar features with gradually varying geometric parameters. Most importantly, the existing artifacts in the literature are only suitable to evaluate the performance of AM processes for fabricating macro-scale parts.

Additive Manufacturing (AM) processes have been recently used as an effective technique for meso- and micro-scale manufacturing [4-5]. Therefore, it's crucial to assess the geometric accuracy and repeatability of meso- and micro-scale features fabricated by AM processes. However, the existing artifacts are not suitable to evaluate the performance of high-resolution AM processes that are used for fabricating micro- and meso-scale features. In this work, we present a novel test artifact design that can be used to both quantitatively and qualitatively test the performance of additive manufacturing processes, particularly for fabricating meso- and micro-scale features. The key features of the proposed test artifact are described to unveil its capabilities of testing the geometric accuracy and repeatability of the AM processes. The proposed test artifact is then used to evaluate the performance of a UV-based additive manufacturing process that utilizes inkjet printing technology. First, the proposed test artifact is fabricated. Next, a number of assessments (both qualitative and quantitative) are carried out to analyze the repeatability, dimensional accuracy, and surface quality of the features on the artifact. Furthermore, a round robin test is performed by using different measurement devices to assure the accuracy of quantitative assessments.

ARTIFACT DESIGN

The proposed test artifact with its key features is shown in Fig. 1. The overall dimension of the test artifact product design is selected to be 46 mm x 50 mm x 3 mm to include all necessary features that will enable evaluation of the limitations and capabilities of AM processes. The artifact is significantly smaller than those presented in the literature. The top surface is considered as the reference surface of the part, which is the primary datum defining the z direction. The substrate thickness of 3 mm is determined as a result of several iterations to prevent any possible warping and to ensure that the reference surface is flat.

The key features of the test artifact model together with their nominal dimensions and purposes for evaluating the performance of AM processes are summarized in Table 1. As depicted in Fig. 1 and summarized in Table 1, the proposed test artifact design includes several simple features such as holes, boss features, walls, pillars, slots with identical geometries and varying aspect ratios to highlight

the limitations and basic capabilities of the AM processes for creating these features within desired accuracy level in a reproducible manner. Many identical features including square pillars array and cylindrical pillars array are embedded in the artifact design to facilitate the repeatability assessment of the AM processes. Furthermore, the features of the artifact are oriented along different directions to test the accuracy of the process in each of the three axes. In addition to these basic features, a few free-form surfaces, based on sinusoidal curves, are added onto this part to investigate the feasibility of AM processes in fabricating features with complex geometries. In addition to relatively large features, fine features are included to assess the accuracy of the processes as well as to obtain minimum attainable feature size. The micro-scale features included in the artifact design have the dimensions down to 80 μm in x and y directions, and the minimum feature size in z direction is 90 μm . These features can be used to highlight the limitations of AM processes in terms of fabricating micro-scale features. Furthermore, some other features such as suspended bridge and T-shape are also included to test the physical properties and mechanical properties of the materials used for additive manufacturing processes.

TABLE 1: Features and Their Purpose for Evaluation.

*Feature	Dimension (mm)	Evaluation Purpose
Cube	3.96x3.96x3.96	Dimensional & positioning accuracy
Cube with cylindrical holes	3.96x3.96x3.96 $\varnothing 2$	Dimensional & positioning accuracy , circularity
Pillars	$\varnothing (0.1 \sim 1) \times (1.2 \sim 3.96)$	Dimensional accuracy, circularity
Holes	$\varnothing 0.08 \sim 1$	Feasibility, dimensional accuracy , circularity
Thin walls	$(0.08 \sim 1) \times 3.96$	Feasibility, dimensional accuracy
Slots	$0.08 \sim 1$	Feasibility, dimensional accuracy
Beams	$0.08 \sim 1$	Feasibility, dimensional accuracy
Staircases	$0.09 \sim 4.02$	Feasibility, dimension accuracy
Square array	$1.5 \times 1.5 \times 2.4$	Positioning accuracy, repeatability
Cylinder array	$\varnothing 1.5 \times 2.4$	Positioning accuracy, repeatability
"V" grooves	90 degree	Feasibility, dimensional accuracy
Complex surface	$y = \sin(x)$	Feasibility, surface quality
Curved walls/slots	$y = \sin(x/2)$	Feasibility, surface quality
Spherical surface	5	Feasibility, surface quality
Suspended T-shape	-	Feasibility
Suspended bridge	-	Feasibility, flatness
Boss / Hollow	-	Concentricity

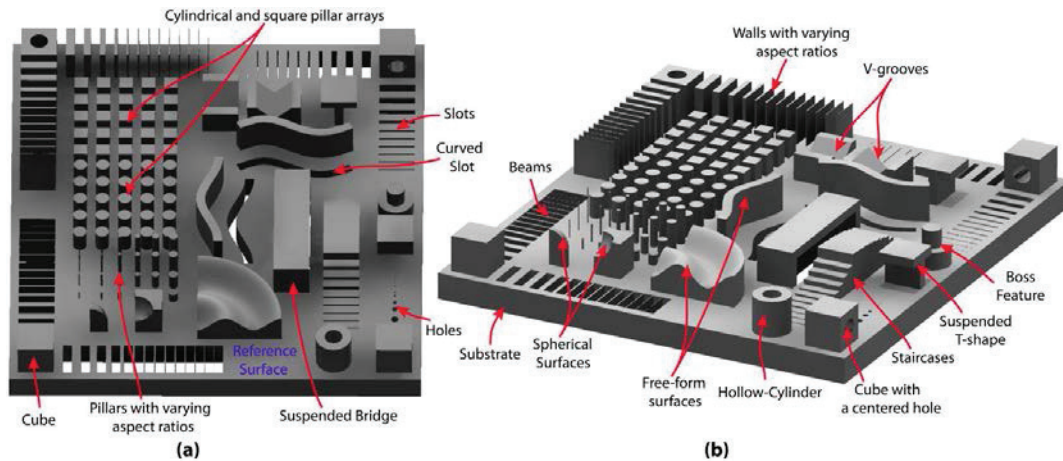


FIGURE 1: The proposed artifact design with its key features: (a) Top view of the proposed design and (b) Trimetric perspective view of the proposed design.

ADDITIVE MANUFACTURING APPROACH

In this study, a high resolution (30 μm) Objet Connex 350 multi-material three-dimensional printing system is used to fabricate the proposed test artifact product. The physical mechanism in this system is photo-polymerization, and the additive manufacturing approach used in this system is demonstrated in Fig. 2. The additive manufacturing approach begins with a 3D model of the object created by computer-aided design (CAD) software. The resulting model consists of closed surfaces to define enclosed volume. The surface model is then converted into the “STL” (StereoLithography) file format that originates from 3D model. The STL file format basically approximates the surfaces of the model by polygons. Next, the specialized software (Objet Studio) slices the three-dimensional model into two dimensional cross-sectional layers, creating a computer file that is sent to the 3D printer system. Finally, the 3D printer system (Objet Connex 350) creates the designed 3D part by adding layers of material with prescribed resolution of 30 μm .

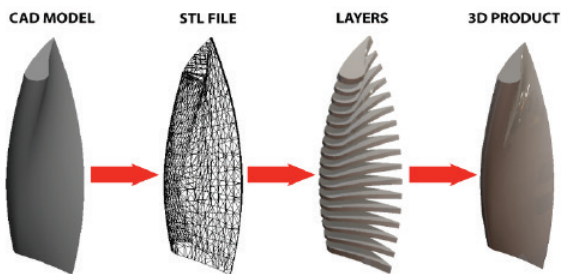


FIGURE 2: Additive fabrication approach.

In the approach summarized above, photo polymerization is achieved by UV-light curing. To create 3D objects, ultra-thin layers (30 μm) are employed layer by layer onto a build tray (350 mm x 350 mm x 200 mm) by inkjet printing technology. During the curing process (turning the fine liquid droplets into solid), a roller mechanism is used to level liquid polymers. Apart from its unique physical mechanism, there are also some optional features of the system which can potentially affect the output quality of the fabricated products. For example, it is possible to build final product with and without support material around features. If the “Glossy” option is selected, the support material is included only to the specific areas to assist the suspended structures. On the other hand, if “Matte” option is selected the entire part is covered by the support material. Hence, it is required to investigate the effect of support material on the output quality of UV-based AM process. It should be noted that it is necessary to remove the support material after the 3D model part is fabricated. Although the suggested way of cleaning support material is using a water jet, it is not suitable for micro-scale features due to high-pressure water which easily breaks the micro-scale features. Therefore, in this study, 2 % NaOH solution is used to remove support material. Furthermore, the AM system used in this work allows using a variety of materials (resins) that can be utilized for fabricating final products. Since the mechanical and physical properties of these materials are different, it is also necessary to investigate the effect of resin material on the output quality of the UV-based AM process.

PERFORMANCE EVALUATION

The proposed test artifact is fabricated by using the AM approach described in the previous section. As shown in Fig. 3, three identical artifacts from three different resins, VeroWhite, TangoBlack, and Digital Material (DM8530) are fabricated with and without support material. Each artifact is fabricated in 30 minutes. Next, the performance of UV-based AM process is evaluated both qualitatively and quantitatively by using the fabricated artifacts.

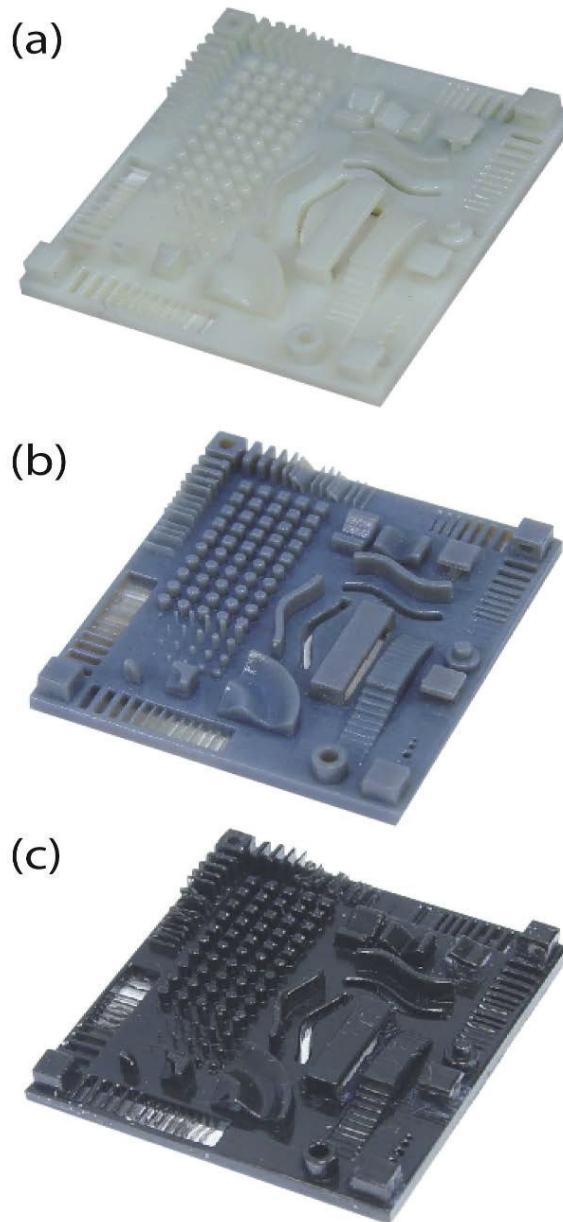


FIGURE 3: The fabricated test artifacts from three different materials: (a) VeroWhite, (b) Digital Material, and (c) TangoBlack.

Qualitative Assessments

Qualitative assessments are obtained using digital camera images and scanning electron microscope (SEM) images to assess noticeable output quality characteristics of the AM process.

In careful investigation of the fabricated artifacts shown in Fig. 3, it is seen that some of the micro-scale features were not successfully created, indicating certain limitations of the AM process and system. For instance, regardless of the resin material used to build artifact, the attainable thickness of the walls with the height of 3.96 mm is 400 μm . The similar limitations can also be seen for holes, pillars, beams and slots. In a nutshell, there are apparent limitations of UV-based AM process for creating micro-scale features, especially with high aspect ratios and with the feature sizes of less than 400 μm .

Three-dimensional free-form surfaces created based upon sinusoidal shape are used to investigate the feasibility of UV-based AM process (see Fig. 4). It is clear that the machine is capable of creating 3D surfaces. These free-form surfaces are fabricated on three materials successfully; this shows not only the geometric but also the material capability of the process.

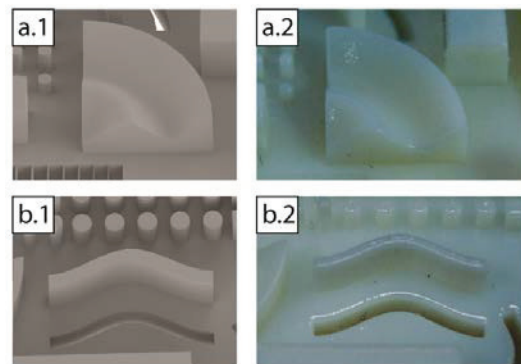


FIGURE 4: Free-form surfaces on VeroWhite material: (a) Designed feature, (b) Final product.

To analyze the surface quality of the created features, the environmental scanning electron microscope (ESEM) images of spherical surface (see Fig. 5) are obtained for two different test artifacts fabricated with support material and without support material. It is seen that glossy finish option (without support material) provides a smooth surface because no support material is covered onto the surface of the feature, and matte finish option that covers the full part with support material results in poor surface quality.

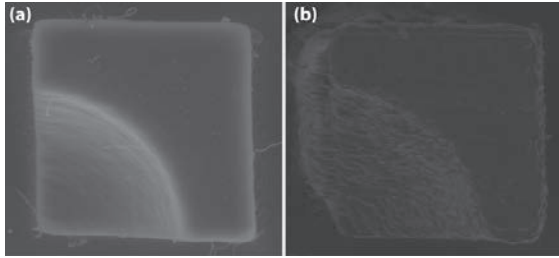


FIGURE 5: Spherical surface feature fabricated (a) without support material and (b) with support material.

Quantitative Assessments/Round Robin Test

Further assessment of the output quality through measurements is then obtained. A round robin test is also performed to assure the accuracy of quantitative assessments. To this end, white light interferometer (WLI), coordinate measuring machine (CMM-see Fig. 6), and environmental scanning electron microscope (ESEM) with Matlab Image Processing Toolbox are used. Prior to any measurements, several points on the substrate surface are measured to check the flatness of the reference surface which can potentially affect the accuracy of measurements.

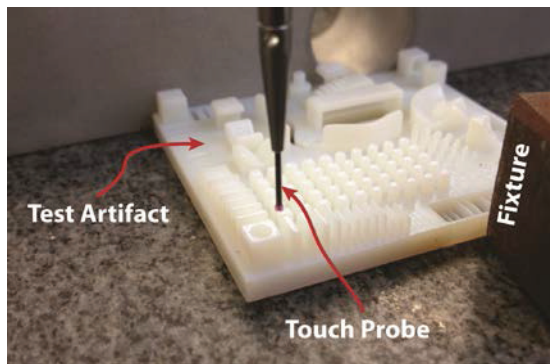


FIGURE 6: The fabricated test artifact in CMM station.

As a part of round robin test, first, the height measurements of staircases are acquired using both WLI and CMM. The obtained dimensions are then compared with the corresponding dimensions on the design. Some of the height measurements of the staircases are listed in Table 2. The first and second value in actual column corresponds to WLI and CMM measurements, respectively. As a result of these measurements, it is concluded that the UV-based AM process is capable of creating staircases with varying dimensions with less than % 10 deviations. It should also be noted

that the accuracy of the process in z direction is a primary function of resolution (minimum layer) thickness and the features having the dimensions of integer multiples of resolution can be fabricated more accurately.

TABLE 2: Height Measurements of Staircases.

Measurement	Design(μm)	Actual(μm)
1	90	86/91
2	180	200/197
3	270	289/286

Subsequently, WLI and CMM are used to obtain the height measurements of square and cylindrical arrays (2400 μm is the nominal value for both). The mean values and standard deviations (SD) of the 25 measurements for each array are listed in Table 3. The first and second value in the columns corresponds to WLI and CMM measurements, respectively. The small difference between nominal and actual values and the small SD values indicate the high accuracy and repeatability of UV-based AM process for features with attainable dimensions.

TABLE 3: Height Measurements of Arrays.

Measurement	Mean(μm)	SD(μm)
Cylindrical	2402/2395	8/12
Square	2406/2392	10/8

Finally, the lateral dimensions of the features in the square array (1500 μm is the nominal value) are obtained using CMM and ESEM with Matlab Image Processing Toolbox. The mean values and standard deviations (SD) of the 25 measurements along x and y direction are listed in Table 4. The first and second value in the columns of the Table 4 corresponds to CMM and ESEM with Matlab Image Processing Toolbox measurements, respectively. The small difference between nominal and actual values and the small SD values indicate the dimensional accuracy and the repeatability of UV-based AM process for features with attainable dimensions.

TABLE 4: Width Measurements of Arrays.

Measurement	Mean(μm)	SD(μm)
Along X direction	1502/1492	6/10
Along y direction	1501/1496	12/9

SUMMARY AND CONCLUSIONS

This paper presented a novel test artifact design that can be used to evaluate the performance of AM processes, particularly for fabricating meso- and micro-scale features. The proposed test artifact model was then used to investigate the output quality of a UV-based AM process that utilizes inkjet printing technology.

The following specific conclusions were drawn from this work:

- The proposed artifact model can be used to highlight the capabilities and limitations of different AM processes for fabricating meso- and micro-scale features.
 - The qualitative assessments are capable of indicating noticeable limitations. Yet, further assessment of the output quality through measurements is required. Also, a round robin test is paramount to guarantee the accuracy of quantitative assessments.
 - The qualitative assessments demonstrate the feasibility of UV-based process for creating features with complex geometries.
 - The qualitative assessments show that the minimum attainable diameter of a hole is 400 μm . Similarly, the minimum attainable thickness of 3.96 mm high walls is 400 μm . As such, the UV-based AM process is not capable of creating micro-scale features such as small-diameter holes and high aspect ratio thin walls.
 - The qualitative assessments indicate that the use of support material in UV-based AM process results in poor surface quality. It should also be noted that it is challenging to clean support material for micro-scale features without damaging them.
 - The quantitative assessments highlight that the UV-based AM process is capable of fabricating features with attainable dimensions in a reproducible manner. The small variations between measurements obtained for round robin test assures the accuracy of assessments.
 - The quantitative assessments indicate that the minimum layer thickness determined by the viscosity and surface tension of the resin material specifies the accuracy of the process in z direction, and the mechanism (roller) used to level liquid (wet) polymers introduce some challenges to create thin and high aspect ratio features.
- Geometric accuracy and surface quality of the fabricated micro-scale features are not suitable for some applications which require fine surface quality and precise dimensions. Therefore, the UV-based AM process should be further improved to attain desired level of accuracy to broaden their fields.

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IN-SITU TARGET SURVEYING FOR INK-JET PRINTING OF FUNCTIONAL MATERIALS

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INTRODUCTION

Ink-jet printing technology has long been used in applications outside of text and image printing on the desktop and in large formats. Examples include medical test chips, display phosphors and backplanes, layers of solar cells, printed circuit elements in general, microlens arrays, adhesive or solder seals and 3D objects.

In ink-jet printing, droplets of ink are generated using thermal or piezoelectric actuators at a close distance above the target surface, typically 0.5-2 mm. Commonly used droplet volumes range from a few pL to over 100 pL, with up to about 1 nL in a few instances. The ink may represent the bulk material to be dispensed and accumulated in the target structure (e.g., microlenses), or the fluid component of a solution or suspension may serve only as a carrier for the material of interest (display phosphors, conducting powders, medical reagents).

Control of the dispensed amount of the material of interest can involve various aspects and methods: ink composition, droplet volume, droplet mass, immediate inspection after printing. Furthermore, correct placement of the dispensed material is an item of serious concern. In some applications, the surface to be printed on is not flat, so some means of feeding surface profile information into the printing process is needed.

Here we will discuss the integration of a laser distance sensor on an ink-jet printer to measure the height of the surface underneath the sensor and thereby the print head. Reading a height at a certain location in the plane can be organized just like placing a droplet, allowing us to handle the laser sensor much like an ink-jet dispenser. Thus our printer architecture lends itself easily to such an extension.

SCANNING THE TARGET SURFACE

We first looked at mapping the surface of a printing target for a project aimed at printing skin components onto large area burn wounds. This involves complex sequences of dispensing living

cells, structural material and nourishing solutions onto the wound. Ink-jetting offers a suitable level of volume dosing per unit area. The shape of the wound surface is not a priori known, so it needs to be measured in time for the application of the reconstructive materials. As the print head must be able to scan over the full area anyway, adding a surveying element for mapping the height profile to the print head offers a convenient way to obtain the needed surface map.[1] The geometric relations between the dispensers and the distance sensor can be determined well and are stable. A concept for a gantry-style surveying and printing system is shown in Figure 1, and the scheme of acquiring a map in Figure 2.

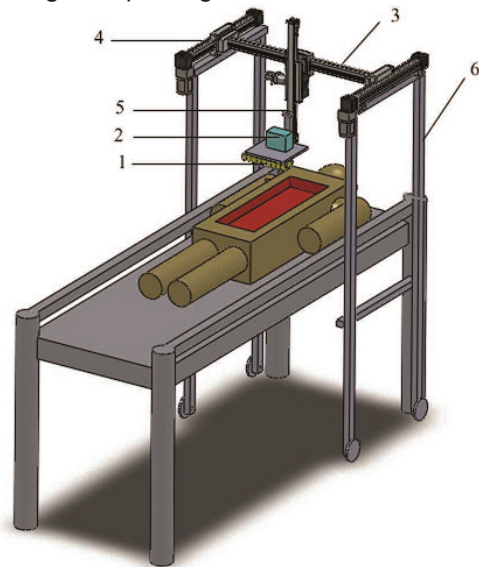


FIGURE 1. Concept for printing skin onto burn wounds. 1: Cartridge-based fluid delivery system; 2: Laser scanner; 3: Mobile frame; 4-6: X, Y and Z axes. (From ref.[1])

While we start out with a compact laser distance sensor that strictly measures only vertical distances, a more complex sensor arrangement with, e.g., 3D laser scanners may become necessary, and a system could take the form of a classic large CMM with both a laser scanner and a print head fitted to its surveying stage (Figure

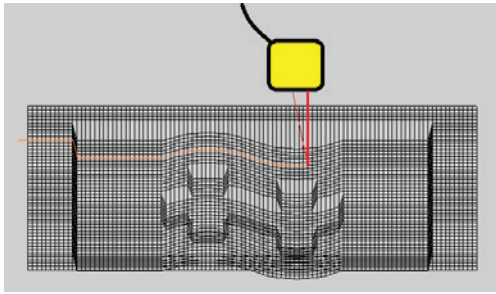


FIGURE 2. Concept of a surface scan, using a target model from ref.[3].

3).[4] In either case, the resolution needed in the height measurement is around or above $100\ \mu\text{m}$, and the laser beam spot sizes, over which some form of averaging occurs, can be of the order of $1\ \text{mm}^2$. To set the application scale, cells can have $20\ \mu\text{m}$ diameter, so placement to about $100\ \mu\text{m}$ is adequate and needs to be accomplished over an area of possibly as large as $0.5\text{-}1\ \text{m}^2$.

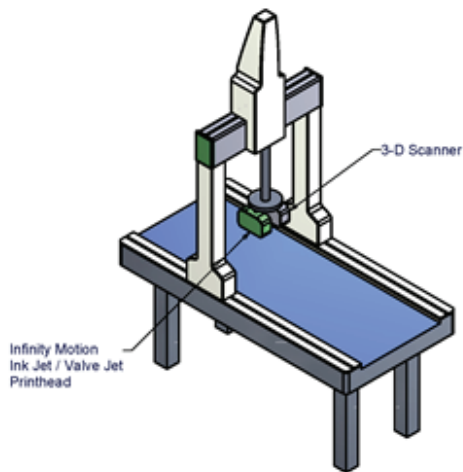


FIGURE 3. CMM with 3D scanner and print head. (From ref.[4])

A detailed print head design for dispensing multiple materials as needed in the skin repair printer project is shown in Figure 4.

The particular application of surveying and printing onto burn wounds has some additional complications (the height or depth of the missing skin tissue must be estimated, and the target can be moving as it belongs to a breathing human[2]), but the concept applies well to printing a priori designed structures (lines, coatings, lenses, ...) on stable inanimate targets (Figure 5).

Integration of a laser scan head can use the same

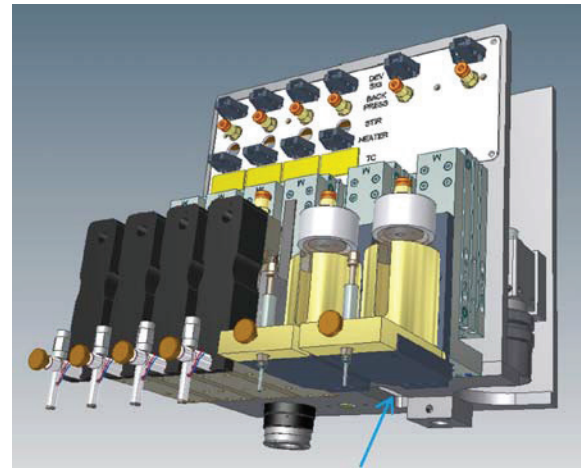


FIGURE 4. Print head for skin repair printing. Each dispenser can be lowered individually for work, in order to otherwise stay clear of any surface structure. The arrow indicates the location for the laser distance sensor for surface profiling.

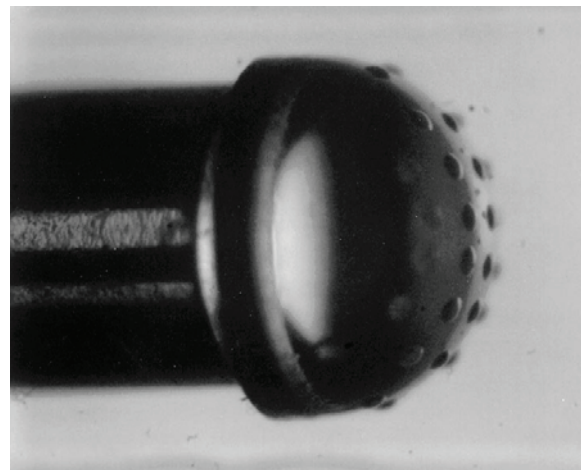


FIGURE 5. Microlenses printed onto a larger lens. No surface mapping was used in this early feasibility test at MicroFab Technologies, Inc., rather, the printhead was kept at sufficient height to stay clear of the target.

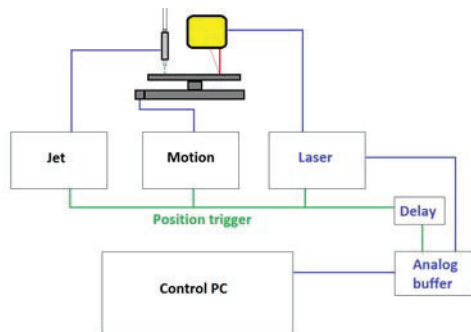


FIGURE 6. Coordination between the motion, laser and jet controllers for acquiring a surface map and subsequently printing on it.

scheme as printing during motion ("on the fly"): The position feedback system produces trigger signals that can be fed to either a print head or the laser scan head (Figure 6). The commercial laser head that we use (Panasonic HL-G108[5]) can hold the readings in analog form until the next trigger arrives, thus allowing for time to convert the analog signal and store it in a buffer (MCC USB-7202 analog I/O module[6]). Once the scan of the object is complete, the control PC of the print station loads the stored data, converts them into print instructions, and moves the print head over the object. Figure 7 shows a move of a laser head over a truncated pyramid that keeps the separation to the surface constant, with the surface shape having been surveyed just before by that laser head moving at constant absolute height. With a full print head assembly like the one in Figure 4 above in place of the bare laser head, a dispenser would move the same way with its tip close to the target surface.

SCANNING THE PRINTED OBJECT

In more conventional printing applications, like printed optics or electronics, the inclusion of a laser distance sensor can be of benefit, too. An example for a printed structure of significant height from an earlier MicroFab project to print lenses from multiple materials is shown in Figure 8.

The available range of performance parameters, in particular the spot size, vertical resolution and repeatability, allows mapping of the shapes of printed objects on top of the target surface. For example, a printed silver line of 50 mm length, desired resistance of $1\ \Omega$, and $250\ \mu\text{m}$ width, would have to have a height of $20\ \mu\text{m}$ or more (requiring multiple passes), assuming a resistivity 6 times

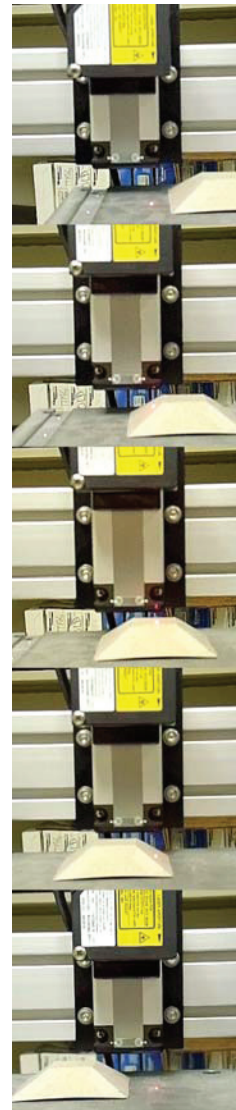


FIGURE 7. Move of the laser head (in lieu of an inkjet dispenser) following the mapped profile it has produced just before.

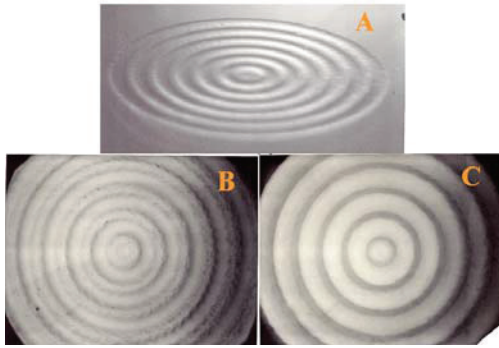


FIGURE 8. Rings of optical material $620\ \mu\text{m}$ wide and $70\ \mu\text{m}$ high. Views: A: perspective at 50° ; B: focused on substrate plane; C: focused on ring-focus plane.

higher than bulk for the printed silver. Thus a sensor with $100\ \mu\text{m}$ spot diameter and $2\ \mu\text{m}$ repeatability, which is commercially available (we use a Panasonic HL-G103[5]), can be applied to control the progress and end point of the printing process (Figure 9).

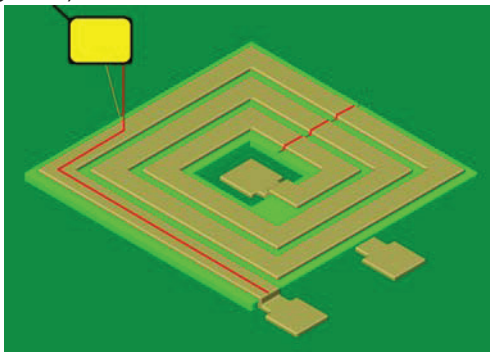


FIGURE 9. Scan of height and width of a printed conductor (adapted from ref.[7]).

A first implementation will use scans across a single conductive line at multiple locations along the line to monitor the cross section, which together with the a priori comparatively well known line length and the material properties determines the total resistance of the line.

CONCLUSIONS

In summary, integration of a laser distance sensor with a print head on an ink-jet printer allows both to establish the actual target surface just in time for printing and the control of the progress and end point in multi-pass printing applications. The fixed geometrical relationship between the coordinate measurement and printing devices reduces registration problems between the two tasks to a minimum. The general benefit to ink-jet printing

of digital control and ability of producing objects in small numbers, down to lots of 1, is extended to changing target shapes and production quality is improved.

Acknowledgements

We gratefully acknowledge discussions with and suggestions from Benjamin S. Harrison of Wake Forest Institute for Regenerative Medicine, and Patrick Cooley, Donald J. Hayes, Virang G. Shah, David Silva and David B. Wallace of MicroFab Technologies, Inc., on the skin restoration project. Donald Hayes also suggested to look at surveying the amounts of material printed. This work was supported in part by funds for the skin restoration project from the U.S. Army Medical Research and Materiel Command, TATRC Grant W81XWH-11-1-0658, and internal funds of MicroFab Technologies, Inc.

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Fusion of Multi-Length Scale CT to Characterize a Pillar Array

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INTRODUCTION

Additive Manufacturing capabilities are reaching the point where it is possible to fabricate single objects with part dimensions ranging from micrometers to meters out of multiple materials. Characterizing the object structure over these length scales increasingly relies on x-ray computed tomography (CT). However, as the material and size ranges continue to increase, the requirements often exceed the capabilities of a single measurement instrument and require the fusion of multi-length-scale and multimodality data. We have developed a range of X-ray CT capability to meet such needs. [1] We describe new X-ray CT capabilities at LLNL to characterize small (micrometer to millimeter) objects with 50 nm to several μm spatial resolution. This work describes the fusion of absorption and phase-contrast NanoCT to characterize the 3D submicron deposition of boron on a silicon pillar array.

EXPERIMENT

The boron coated silicon pillar array is shown in Figure 1. The array was fabricated by etching a Si substrate and coating the 2D pillar array with a boron coating. The boron coating thickness varies both laterally and vertically and ranges from $0.2\ \mu\text{m}$ to completely filling the $2\text{-}\mu\text{m}$ gap between pillars. The boron-silicon system serves as a test case for analyzing highly mismatched materials ($\mu_{\text{Si}} = 27 \times \mu_{\text{B}}$ where μ is the X-ray attenuation coefficient at 8 keV).

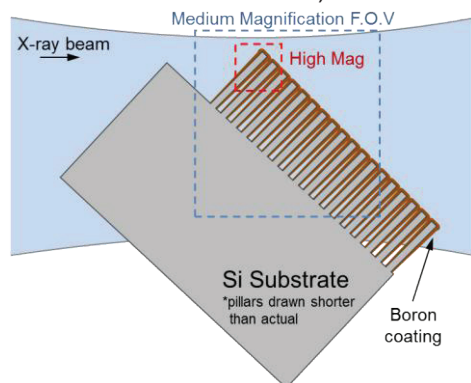


FIGURE 1. Diagram of the B and Si test object. The medium and high spatial resolution (mag.) was obtained using the UltraXRM.

The test object was imaged by the Non-Destructive Evaluation Group at LLNL using two commercial Xradia systems. The first, a MicroXCT-200 for low spatial resolution ($\sim 7\ \mu\text{m}$), used an 80-kV bremsstrahlung spectrum to image the full 1-cm object. The second, an UltraXRM L200 [2] used a quasi-monochromatic 8-keV beam to image the object in both the X-ray absorption and X-ray phase-contrast projections. The UltraXRM provides medium ($\sim 200\ \text{nm}$) and high ($\sim 50\ \text{nm}$) spatial resolution CT data.

RESULTS

The CT results were analyzed to determine the boron fill fraction, which is defined as the ratio of boron volume to available volume between the silicon pillars. Absorption and phase-contrast cross-sectional images are shown in Figure 2. we analyzed these images separately to determine the silicon volume and the combined silicon-boron volume, respectively. The multi-length-scale, multi-modality images are registered using *in-situ* gold microspheres and a least-squares based algorithm.

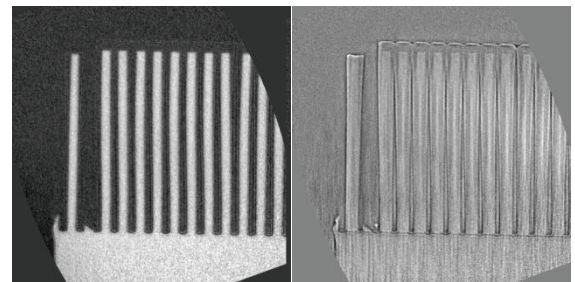


FIGURE 2. Comparison of medium magnification ($\sim 200\ \text{nm}$ res.) absorption (left) and phase-contrast (right) cross-sectional UltraXRM images.

Since CT cross-sectional images contain partial volume artifacts, the critical first step is determining the optimal threshold for surface extraction and binarization. The high magnification (high res.) threshold is set at the inflection point for the absorption and phase-contrast images to segment the Si and Si+B volumes. After segmentation the volumes were determined. The high resolution volumes were

compared to medium resolution volumes and the medium resolution threshold was adjusted to generate equivalent volumes (Figure 3). We attempted the volume comparison for larger regions using the medium- and low-resolution CT images, but this did not work well.

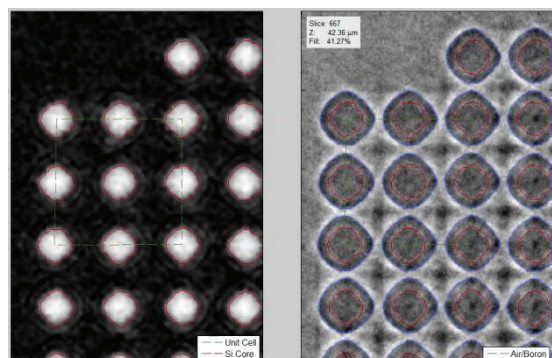


FIGURE 3. Comparison of absorption (left) and phase-contrast (right) horizontal cross-sectional UltraXRM medium mag. images. The Si/B and B/air segmentation results are shown in red and blue, respectively.

Quadrilateral unit cells are defined from the pillar centroids and the 3D fill factor is computed throughout regions of interest. A representative 2x2 unit cell (shown on the left in Figure 3 by the green dotted box) fill factor was computed and is shown in Figure 4.

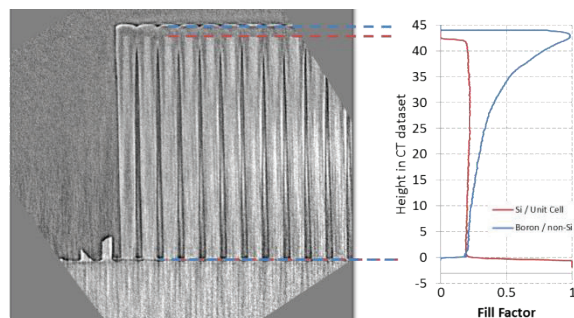


FIGURE 4. A representative fill fraction over a 2x2 unit cell.

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ACKNOWLEDGEMENTS

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Comparability of the performance of in-line computer vision for geometrical verification of parts, produced by additive manufacturing

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ABSTRACT

The field of Additive Manufacturing is growing at an accelerated rate, as prototyping is left in favor of direct manufacturing of components for the industry and consumer. A consequence of mass-customization and component complexity is an adverse geometrical verification challenge. Mass-customized parts with narrow geometrical tolerances require individual verification whereas many hyper-complex parts simply cannot be measured by traditional means such as by optical or mechanical measurement tools.

This paper address the challenge by detailing how in-line computer vision has been employed in order to verify geometrical tolerances. The paper addresses to which precision, tolerance verification has been achieved, by assessing the reconstruction capability against reference 3D scanning by a selected number of AM processes. Geometrical verification was achieved down to a precision of 20 μ m for ideal AM processes, whereas the thermally driven SLM due to thermal warpage, resulting in a reconstruction accuracy of 400 μ m.

INTRODUCTION

The field of Additive Manufacturing(AM) is growing at an accelerated rate, and from the previous application as a prototyping technology toward direct manufacturing of net-shape components for industrial and consumer goods. Driven by this mechanism is an extended application of mass-customizable components, as well as hypercomplex components that by traditional manufacture would have required an additional structural breakdown into smaller, simpler components in order to be produced[1].

A consequence of mass-customization and component complexity is an adverse geometrical verification challenge. Mass-customized parts with narrow geometrical tolerances require individual verification whereas many hyper-complex parts simply cannot be measured by

traditional means such as by optical or mechanical measurement tools.

HYPOTHESIS

This paper address the challenge by detailing how in-line computer vision has been employed in order to verify geometrical tolerances on powderbed- and resin based industrial AM platforms.

A flexible computer vision system has been developed in order to allow for image capture of each individual layer as parts are manufactured. From image data, the additively manufactured three-dimensional geometry can be extrapolated. The extrapolated geometry can be used for tolerance verification against the CAD body in a very similar manner to that of verification by means of 3D scanning. The advantage of the inline system is that given the layered capturing scheme employed by the in-line vision system, any hyper-complex geometry can be reconstructed.

Given all industrially applicable AM processes are layered, a generic geometry reconstruction method has previously been suggested[2], where each layer is inspected prior to addition of succeeding layers by means of computer vision. If each layer can be characterized in a manner so that the boundaries of the geometry within each layer can be found, as shown in *FIG. 1*, and the layer-height of the build-job is known, a three-dimensional model can be meshed from the accumulated data gathered during a build-job. The hypothesis is, that this three-dimensional mesh can be used as a means of tolerance verification.

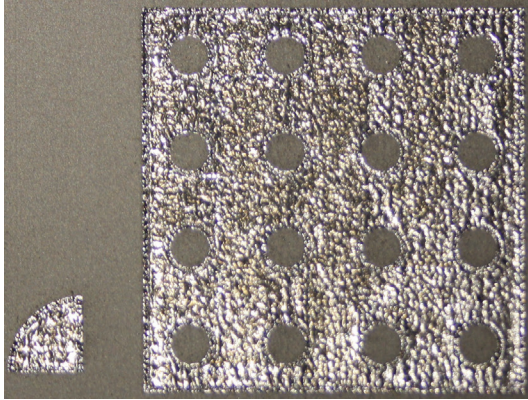


FIGURE 1. Image Capture during the build-job of a calibration plate and calibration sphere.

This way of verifying geometries does not come effortlessly as there with most AM processes is a tendency for the accumulation of stresses within the manufactured structures as the AM build-job progress. These stresses result in geometrical deformations, and the challenge is that the exposed and just deposited layer that was characterized by the computer vision system will have altered its geometry when the build-job is completed. Furthermore, in resin based AM processes, it is a challenge in itself, to distinguish the visual difference between structure and uncured photo-polymer.

It is thus needed to understand to what extend stress-deformations, and challenges related to the visual characterization will impact the geometrical reconstruction from image data, and as such this is the main aim for this paper to clarify. This is done in order to set the foundation for further development of a system based upon computer-vision that is fully capable of reconstructing any geometry from any AM process, with an accuracy that is comparable to tactile-, optical- and optomechanical verification methods.

A fundamental question arise, as to how a computer-vision system can be developed to an extend from which warpage from stress-deformations can be quantified. It is believed that a sole implementation of said vision-system will not be able to recreate true-to-geometry reconstructions from thermal processes such as SLM. It will however be possible to extrapolate the 2D geometry for each undeformed layers, prior to addition of the succeeding layers. This will directly yield sufficient data to assess whether defects of internal geometries are present. These e.g. being inclusions visually

present from one or more of the inspected layers or the collapse of weakly supported features.

Within these processes where stress build-up is prevalent, such as with SLS and SLM, a superimposed numerical warp analysis of the relaxed geometrical reconstruction, from known boundary conditions (process and vision-data) is believed to yield a fair accuracy of reconstructed geometries. The latter will not be addressed within the scope of this paper. Finally, it has already been concluded that many AM processes introduce so little stresses in manufactured geometries, that the relaxed representation given from said computer-vision system will yield a fair accuracy of reconstructed geometries. [3]

METHOD

The paper addresses to which precision, tolerance verification has been achieved, by comparing the reconstruction capability against reference 3D scanning by a selected number of AM processes. From this analysis it is shown and concluded that the tolerance verification capabilities of computer vision within AM is a fast, efficient and for some AM processes, accurate method for securing manufacture to tolerances for mass-customized and hyper-complex geometries.

Platforms

The industrial AM platforms in subject for this study are:

- **zCorp 310/zCorp 650**, building parts in a powder-bed from a plaster-based (CaSO_4) proprietary material by a non-thermal binding scheme
- **Realizer SLM 250**, selectively melting metal powders ranging from stainless, (316, 304L, 309, 174), over maraging steel (M300) to titanium alloys(6Al-4V) to form solids by employment of an industrial laser.
- **EnvisionTEC Perfactory MML**, DLP platform that employs photo-initiated polymerization of acrylate based resins to form solid geometries by means of exposure masks.

Vision System & Positioning

The camera employed is a Canon EOS 1000D with a EFS 18-55mm f/3.5-5.6 IS lens kit, calibrated against a checkered calibration plate.

The positioning of the computer vision system used for data capture has been tailored to the chosen platforms. For the two powder-bed based processes, the camera has been positioned above the build chamber, as close to a right angle as possible. A right angle is easily achieved in the zCorp platform, whereas a compromise had to be found for the Realizer platform, as seen in *FIG 2*, to avoid obstruction of the optical path of the processing laser.

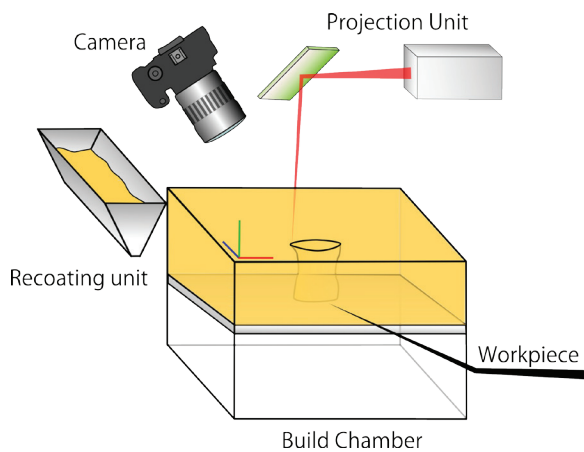


FIGURE 2. Camera position in the Realizer SLM 250.

The angular deviation result in a skewness of the captured image data that is corrected for, by employing camera calibration[4]. Whereas an angular deviation must be compensated for when introducing the vision system to an SLM platform, the task of determining a suitable camera position for the EnvisionTEC platform is much more complicated.

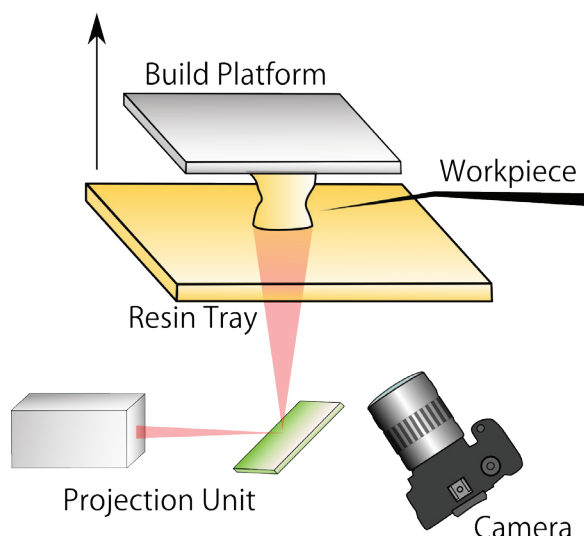


FIGURE 3. Camera position in the EnvisionTEC Perfactory MML.

A position below the resin VAT was chosen. This position did allow for an unobstructed exposure of the photo-polymer at an acute angle to the camera. The obvious challenge was to distinguish structure from uncured photo-polymer, as there was no difference in color, hue, tone or refraction noticed. The chosen solution was thus to study the UV light emitted directly off of the projection unit. This light will reflect back into the camera with a primary reflection from the underside of the glass VAT, and a secondary reflection from the upperside of the VAT. Attention was drawn toward the upmost reflection, as this comes straight from

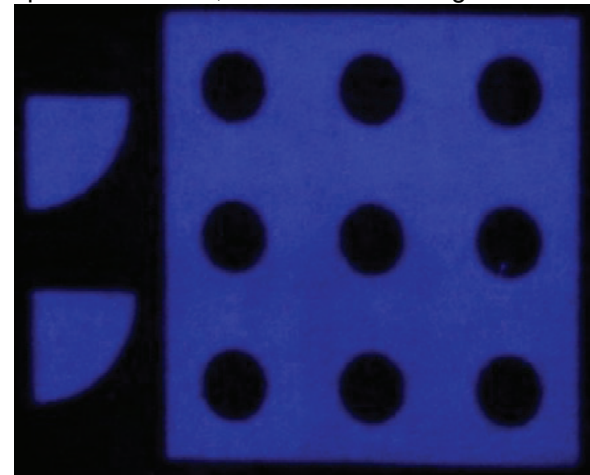


FIGURE 4. Capture of the secondary reflection of the VAT by means of a circular polarization filter.

the contact-interface between the VAT and the manufactured structure. This reflection could be insulated using a circular polarization filter, as seen in *FIG. 4*, and was chosen to represent the polymerization occurring inside the VAT.

RESULTS

Two test geometries had been chosen with inspiration from the art of geometrical metrology. The two chosen geometries has a proven reputation as calibration artifacts, and as machine calibration geometries. These are the sphere and the hole-plate[5][6].

Each object was manufactured by the selected AM platforms. The objects was scaled to fit within the optimum build-envelope of each machine. This mean that the geometry has been printed to different scale, (see *FIG. 5*) according to the machine specifications, and that all results thus has been normalized.

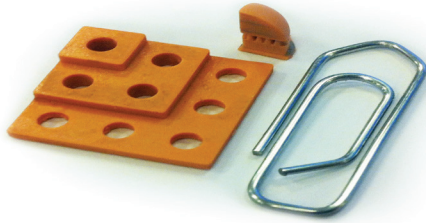
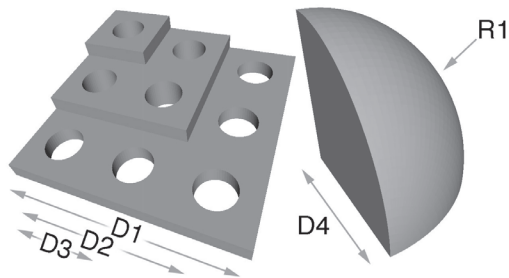


FIGURE 5. Test geometries manufactured with the EnvisionTEC Perfactory MML.

The normalized measurements seen in FIG. 6 was used to assess how well the vision system performed according to platform.



AM Platform	D1	D2	D3	D4	R1	Error in %
zCorp 650	.13	.11	.13	.15	.14	
Realizer 250	2.7	2.9	3.2	2.8	3.0	
EnvisionTEC MML	.11	.11	.14	.11	0.12	

FIGURE 6. Vision System versus reference measurements on accredited CMM.

The errors in ‰ represent the deviation from reference measurements conducted by accredited CMM measurements on a Carl Zeiss OMC 850. Absolute Deviations according to platform can be seen in the table below:

TABLE 1. Absolute Deviations pr. platform

	zCorp 650	Realizer 250	EnvisionTEC MML
Max	$\pm 19 \mu\text{m}$	$\pm 371 \mu\text{m}$	$\pm 11.3 \mu\text{m}$
Min	$\pm 7 \mu\text{m}$	$\pm 89 \mu\text{m}$	$\pm 12.1 \mu\text{m}$

From table 1, it can be seen that there is an agreement of $\pm 20 \mu\text{m}$ between the vision system and reference CMM measurements. The quality of these result are linked to the fact that the zCorp 650 employs a cold deposition of a binder agent to the proprietary plaster-based powder. As such it is a process inducing very little accumulation of stresses within the manufactured geometry. Hence, if the vision system successfully extrapolate geometry, this can be considered unaffected by deformations as the build-job progresses. The trend is directly opposed with respect to the Realizer 250. A high accumulation of thermal stresses induce a high degree of warpage of the final part. Therefore, it is not possible to determine

the geometry to a satisfactory degree. Finally, it was possible to determine the geometry built with the EnvisionTEC down to a mere $\pm 12 \mu\text{m}$. It must however be mentioned that the EnvisionTEC was running the job with a $16 \mu\text{m}$ voxel mask resolution, and that the quality of the measurements are near the specifications of the AM platform. This makes error identification difficult This not least when it is considered that reconstruction has not been performed from image data of the manufactured structure itself, but the reflection of the light emitted in order to cure the photo-polymer.

DISCUSSION

The aim of this study was to illustrate the applicability of computer vision as a means of geometrical verification within Additive Manufacturing. Experiments showed that geometrical reconstruction from layered image data is possible and that this can be achieved down to $\pm 20 \mu\text{m}$ for non-thermal powder-bed systems. This is considered to be within the tolerance range to where the vision system is readily applicable as a geometrical verification tool For the SLM process, tolerance verification could be achieved within $\pm 371 \mu\text{m}$. Though SLM is considered a near-net-shape manufacturing technology, and precision-manufacturing by SLM often involves a post-processing step by machining, it is believed that a much better reconstruction from image data can be achieved by superimposing a warp analysis over the raw image-based geometry reconstruction. Finally it was possible to achieve geometry reconstruction from the EnvisionTEC MML platform down to $12.1 \mu\text{m}$. This is though very close to the EnvisionTEC's resolution, and as such it is preferable if a true macro-lens camera system could be employed in future tests. Furthermore it must be remembered that the reconstruction has been made based upon a reflection of the UV light used to cure the photo-polymer. A more ideal approach to capture image data is if the geometry itself can be observed by the vision system.

FUTURE WORK

It is believed that computer vision can be tailored to be suited as an in-line geometry reconstruction system for AM processes. Challenges are obvious, and range from thermal stresses to the detection of structure from surroundings. If these challenges are met, it will be possible to equip any common additive manufacturing platform with an inexpensive yet highly capable vision-system for direct verification of each mass-customized or tailored geometry that will be manufactured on the vision-equipped platform. Thus, research will be continued by the authors in order to advance one step further toward this goal.

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METROLOGY CHALLENGES OF PARTS PRODUCED USING ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing (AM) processes provide a variety of optimization opportunities using the enlarged space of designs previously inconceivable using traditional subtractive manufacturing methods. Along with these design freedoms come significant complications for the metrology of parts produced using AM, as increases in design complexity may make traditional measurement of many features prohibitively time-consuming, difficult, or even impossible to perform non-destructively. Surface mapping using touch probe or 3D scanning methods is suitable for the measurement of complex surfaces and simple topologies, but provide limited utility in assessing internal structures or other features hidden by more complex topologies where an interior structure is obscured. An example of such internal structure is illustrated in Figure 1, showing a view of infill structures which are not externally visible.

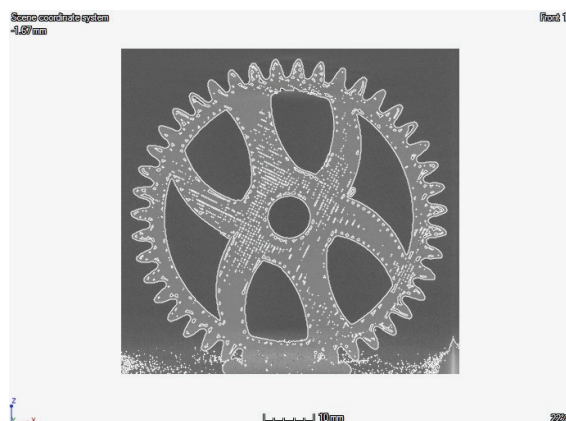


FIGURE 1. Cross section view of printed polymer herringbone gear showing interior infill support structures.

X-ray computed tomography (CT) provides a more robust method for the non-destructive evaluation of both internal and external surfaces by providing a voxel-based volumetric map of an effective radiographic absorption coefficient, which may be used to reconstruct the object surface even in the case of multi-material objects [1,2,3]. The absorption map for a DMLS dogbone can be seen in Figure 2, prior to any surface reconstruction.

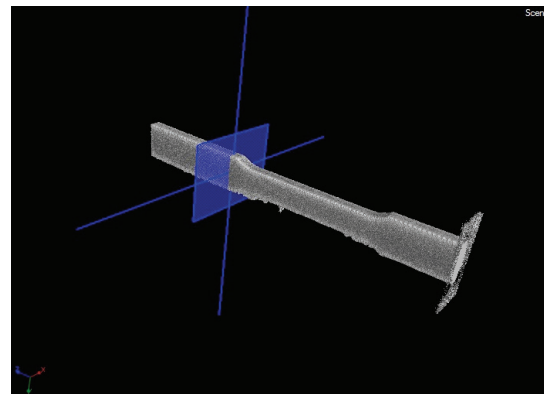


FIGURE 2. DMLS dogbone CT data prior to surface reconstruction, with residual support structure underneath.

Surface reconstruction provides a means for assessing the dimensioning and tolerance over the entire design (internal and external) using a direct comparison applied between the reconstruction and the original CAD model used to manufacture the reconstructed object. Surface reconstructions also provide a basis for other techniques traditionally applied to CT data (defect analysis, part-to-part comparisons, porosity analysis, reverse engineering, etc.) which are often relevant to the qualification of AM parts and processes more broadly.

This work applies several of these analytical X-ray CT approaches for the inspection and qualification of polymer and metal objects created using a variety of AM processes including direct metal laser ‘sintering’ (DMLS), laser engineered net shaping (LENS), and fused filament fabrication (FFF), with a particular emphasis on defect detection, density/porosity analysis and geometric dimensioning using surface reconstruction comparisons, as shown in Figure 3. The range of applicability of this technology, as well as its limitations and potential for use in the inspection of AM parts will be discussed.

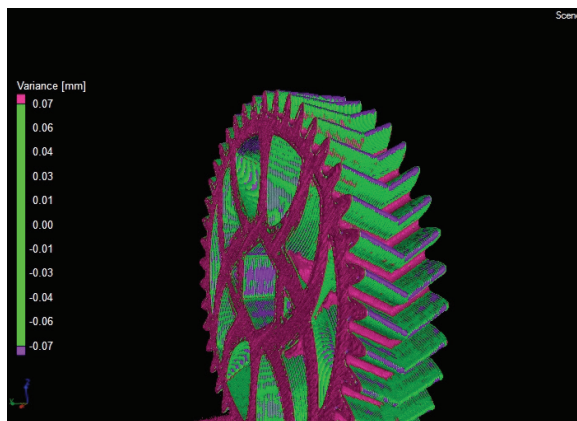


FIGURE 3. Surface comparison of FDM/FFF herringbone gear. The peaks and troughs of the teeth can be seen to deviate more than 0.07mm from the expected surface defined by the model.

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IDENTIFICATION OF MECHANICAL AND FATIGUE CHARACTERISTICS OF POLYMERS FABRICATED BY ADDITIVE MANUFACTURING PROCESS

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INTRODUCTION

Additive Manufacturing (AM), more commonly known as 3D printing, is the process of building a product or part by applying materials or powders in very thin layers, until the final product has been built. This capability allows for a variety of new design possibilities for AM such as hinge-based mechanisms, shock absorbing castings, integrated gaskets, and so on [1-3]. The process starts with a 3D model in an STL format, which is imported into the AM software. The AM software converts its geometry into horizontal slices in the form of multiple layers with varying thicknesses. Many processes include the use of UV, laser, or thermal-associated technology; such as Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), and Stereolithography (SLA) [1]. Materials commonly utilized in AM range from resins and polymers to steel.

Recently, a number of AM-based devices for precision sensing and actuation applications have been introduced [2,3]. However, the stability characteristics of devices fabricated by AM processes are not well understood and there is very little to indicate what the dominant manufacturing parameters are, how creep and fatigue are affected by different processes and materials, and how to design for stability. For the general aspects of polymer fatigue, the interested reader is referred to a few excellent reviews and articles that adequately cover much of the recent polymer fatigue research on life time [4,5], fatigue crack propagation [5-7], cyclic softening [8,9], thermo-mechanical effects [10,11], fracture surface morphology [12], processing variables [13,14] and cumulative damage models [15]. Here the physical testing

for identifying mechanical and fatigue characteristics including tensile strength and high and low cycle fatigue is conducted in accordance with the applicable ASTM standard.

MECHANICAL CHARACTERISTICS

Mechanical characteristics of the 3D printed polymeric specimens were identified by using a tension test machine while measuring the applied force and strain. The geometry of the specimen was determined according to the ASTM test standards: 150mm long, 20mm wide and 3mm thick. The test specimens were fabricated by FDM process under 32 printing conditions. Five print settings were varied for testing including layer thickness, extrusion width, printing orientation, feedrate and distance between beads as summarized in TABLE 1.

TABLE 1. *Printing conditions.*

Factors	Condition I	Condition II
Material	Acrylonitrile Butadiene Styrene	
Extruder temp. [°C]	200	
Bed temp. [°C]	100	
Layer thickness [mm]	0.2	0.3
Extrusion width [mm]	0.35	0.45
Print orientation [Deg.]	0	90
Feedrate [mm/min]	2000	4000
Distance btw beads	0	-0.1

Three sets of each test specimen were fabricated under the same printing conditions, respectively, which indicates that a total of 96 test specimens were tested to obtain the

mechanical properties of the polymeric material fabricated by the FDM AM process.

As a result, the test specimen fabricated under 0° printing orientation and small layer thickness showed a high strength, 36.3 MPa. While, other printing conditions, feedrate and distance between the beads, did not have a significant influence on the material strength as seen in FIGURE 1. In the hereafter, analytical approaches with finite element analysis will be applied for identification of material properties [16].

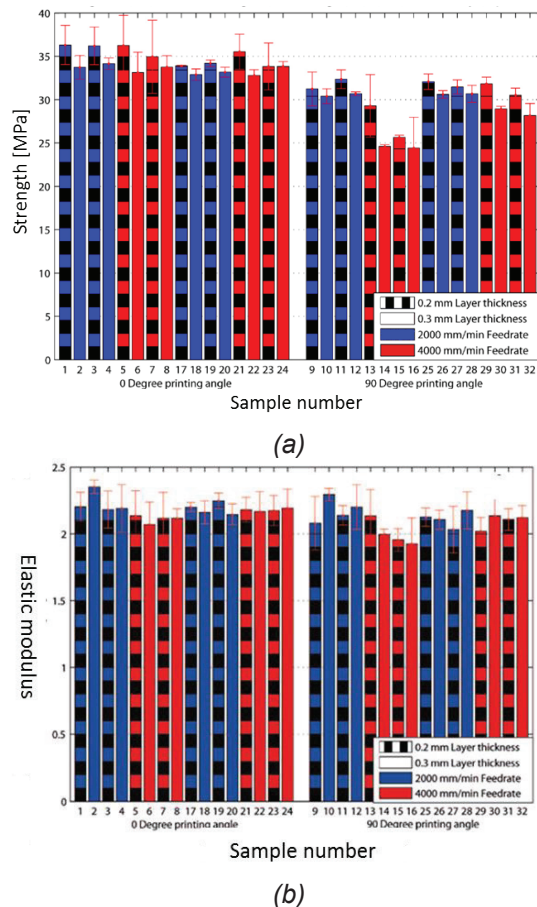


FIGURE 1. Results of the averaged maximum material strength (a) and elastic modulus (b) of 96 test specimens.

TABLE 2. Printing conditions.

Configuration number	#1	#2	#3	#4
Layer thickness [mm]	0.2	0.3	0.3	0.2
Extrusion width [mm]	0.35	0.45	0.35	0.35
Print orientation [Deg.]	0	90	90	0
Feedrate [mm/min.]	2000	4000	2000	4000
Distance btw beads	0	0	0	0

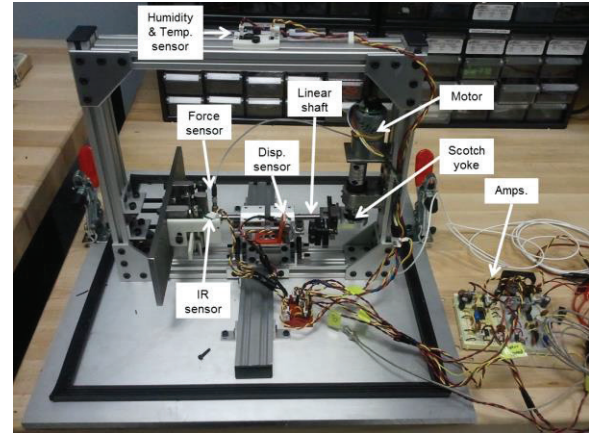


FIGURE 2. In-house built flexural fatigue test machine.

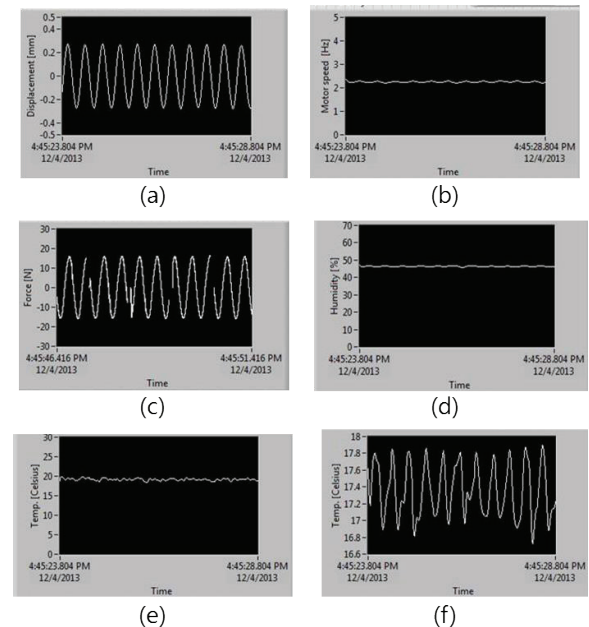


FIGURE 3. Summary of data acquisition: (a) displacement, (b) loading frequency, (c) force, (d) humidity, (e) global temperature, and (f) local temperature at cyclic force loading zone of the sample.

FATIGUE CHARACTERISTICS

As an early stage of research, the fatigue characteristics of the test specimens fabricated by an AM process were identified by using the in-house built fatigue test machine (FTM, 350mm X 350mm), which was designed in accordance with ASTM D7774-12, the standard test method for Flexural Fatigue Properties of Plastics as seen in FIGURE 2 [17]. The in-house built FTM utilizes a scotch yoke mechanism, which is a reciprocating motion mechanism to

convert the rotational motion of a motor into linear motion [18]. Therefore the shape of the motion of a linear shaft connected with a DC motor is a pure sine wave over time given a constant rotational speed; this enables the application of time-varying cyclic loads on the test specimen. A load cell is mounted between the end tip of the linear shaft and the test specimen. A thermopile IR sensor is placed close to the area where the cyclic load applies and used for non-contact surface temperature measuring at the loading zone locally because fatigue crack propagation leads to heat dissipation [19]. Also, relative humidity and global temperature are monitored at the same time. All the data are collected with LabView DAQ board and monitored in real time as presented in FIGURE 3.

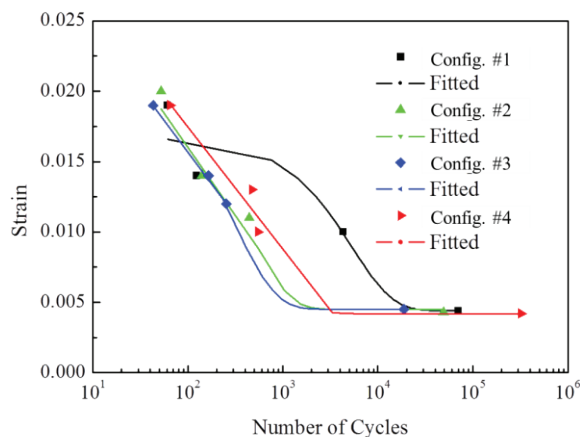
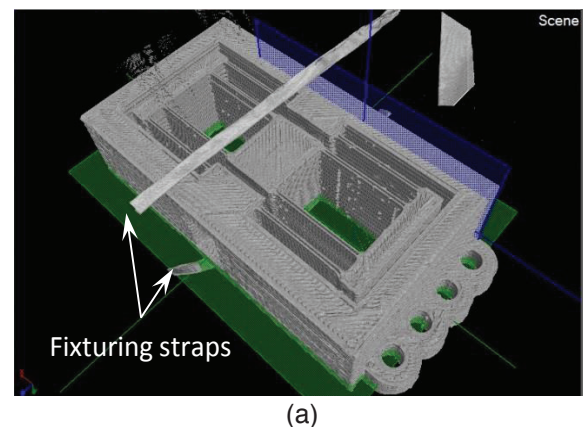


FIGURE 4. Results of fatigue test.

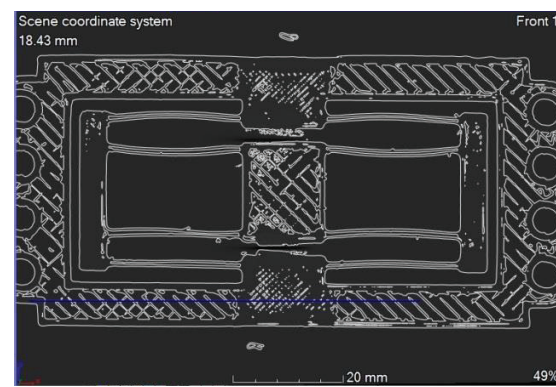
The four configurations fabricated under the printing conditions shown in TABLE 2 were prepared and tested in the FTM. The configurations were selected based on the results of FIGURE 1, which illustrates a significant difference of material properties according to varying printing conditions i.e. layer thickness, extrusion width, print orientation, and feedrate. The printing orientation of 0° corresponds to printing parallel to the length of the sample.

The strain rate of each sample was calculated from the displacement measured by the built-in displacement sensor. The results of the fatigue tests are presented in FIGURE 4. Four strain rates were plotted for each configuration with respect to the number of cycles until failure and curve-fitted by an exponential function. Failure was determined according to the ASTM specification as the point

at which the load on the sample decreased by 10% of the original load. Each configuration contains four sample tests at different strain rates. It should be noted in FIGURE 4 that even at strain rates as low as 0.5% the ABS specimens do not reach an endurance limit. Failure at this strain rate comes at 20,000-40,000 cycles for Configurations 3 and 2, the 90° conditions, and at 70,000-320,000 cycles for configurations 1 and 4, respectively, which are the 0° conditions. Continuing tests are being performed at lower strain rates to understand the endurance limit for these ABS specimens. From the results of the preliminary fatigue test, it can be seen that the print orientation, layer thickness, and feedrate have a significant influence on the fatigue among the printing parameters.



(a)



(b)

FIGURE 5. CT Images of the AM-based flexure stage (a) and its cross-sectional view (b).

Based on the preliminary results, the systematic experimental procedure will be carried out under controlled conditions in order to discover an unknown effect and illustrate a known effect at the same time. Design of Experiments (DOE) will be used to evaluate

which process inputs have a significant impact on the process output, and what the fatigue level of those inputs should be to achieve a desired output. Four main process inputs, layer thickness, extrusion width, print orientation, and feedrate, will be subdivided into two-level and the relationship between strain and number of cycles will be empirically found.

For the further work, the progressive and localized structural damages will be tracked by Computed Tomography (CT) scans (See FIGURE 5), and then, the CT images before and after fatigue testing will be used to obtain quantitative estimates for the residual internal deformations and the spatial distribution of the deformations by using volumetric digital image correlation technique [20]. These results allow the identification of the fatigue and reliability characteristics of the polymeric materials fabricated by the AM process under various printing conditions and allow for the comparison between well-documented theoretical models for bulk materials to experimental results. Furthermore, a theoretical model based on nominal strain amplitude for the fatigue life prediction of the compliant polymeric material will be developed.

CONCLUSION

The methods to identify the mechanical properties and fatigue characteristics of polymeric materials fabricated by an AM process were discussed. It was seen that the AM-based polymeric material properties are significantly dependent on the printing conditions, and those fatigue characteristics are expected to be different from those of bulk materials. The fatigue model based on S/N curves, stress-strain curves and cohesive model will be developed from the results obtained from the mechanical tests and CT scans. It will be used to understand the fatigue behavior and more accurately characterize the mechanical response of a polymeric material for various AM applications.

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OPTIMIZATION OF SLM STRUCTURES WITH RESPECT TO CRACK GROWTH AND LIFETIME

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INTRODUCTION

First machines for Additive Manufacturing (AM) have already been introduced in the 80s. Many reasons have led to optimize the whole process chain for example low build-up rates, low resolutions, inadequate surface quality as well some material properties [1,2]. Since then, the development of machines have been continued [1,3]. For a long time this process has been mainly used for the manufacturing of prototypes. The ongoing improvement and the promising outlook for the future [4] made the AM process an attractive hot topic of research and industry.

Additive Manufacturing is characterized by material efficiency and a short time to market for AM components:

- Material efficiency is realized by part constructing, only in areas which are defined as volume partition according to the CAD model. In some AM processes like SLM the excess not fused powder material can be filtered after the end of a job and reused in further building- operations.
- By using direct manufacturing of parts from a CAD model, there is no need for the development and manufacturing of tools or casting molds. Consequently, the time to market is decreased.

During the additive manufacturing process Selective Laser Melting (SLM[®]) produced by SLM Solutions, the powdered base material is fused after exposing by laser. The melting pool is only in a small local range. Hence, layer-by-layer manufacturing of components is possible as shown in Figure 1. The fabrication of parts by SLM is reiterative process that is carried out in three consecutive steps as follow: coating, exposing, lowering.

Despite the numerous advantages and unique features of the AM process, the success and implementation of these technologies depend mainly on their behavior under loading. Thus, there is an acute need to examine AM materials and to optimize them.

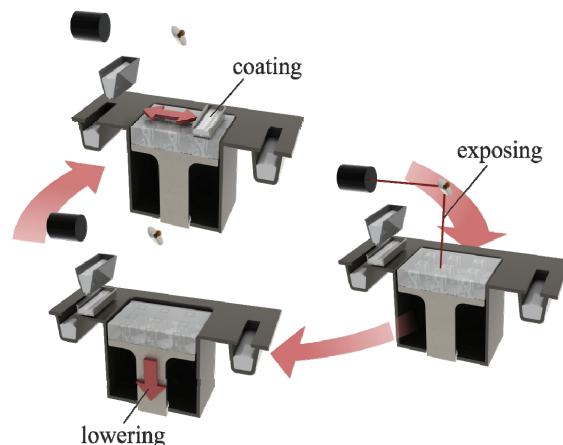


FIGURE 1. Basic steps during SLM-process.

The focus of the present work is on studies of compact tension specimens processed of titanium alloy Ti-6-4. The samples analyzed in this work were manufactured by SLM. The challenge of this study is to improve fracture mechanics properties with regard to material processed by standard routes. For this reason, the compact tension (CT) specimens were subjected to various heat treatments. Based on these findings the software tool NASGRO was used in order to analyze the resultant service life time. For this purpose one represented part was selected.

EXPERIMENT

In order to manufacture the CT specimens of titanium alloy Ti-6-4 the selective melting machine SLM250^{HL} from SLM Solutions was deployed. The mounted laser is an yttrium fiber laser with a maximum power of 400 watts. Data preparation for the selective melting machine was performed by the commercial software SLM AutoFab (Marcam Engineering). The layer thickness was 30 μm . In order to avoid powder contamination with oxygen and nitrogen the build chamber was filled with argon. The average powder particle size is given by 40 μm .

Specimens with perpendicular as well as parallel initial crack orientation in relation to the build direction were manufactured in order to make conclusions about material isotropy. Figure 2 shows Ti-6-4 plates for CT specimens. The final contour was machined according to ASTM E 647-08 [7] after the SLM process was finished.

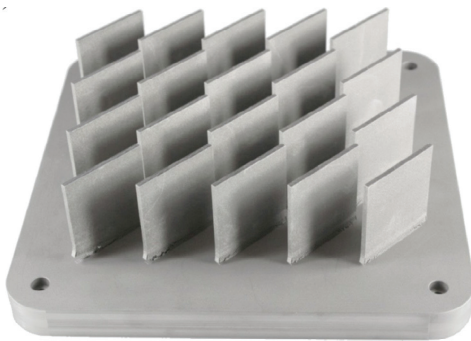


FIGURE 2. Plates for CT specimens for perpendicular and parallel directions.

Table 1 contains parameters for different cases of heat treatment to which the CT specimens were subjected. These cases were used in quasi-static tests and delivered optimum values for tensile strength, yield strength and elongation at break and were thus selected for fatigue testing [6].

Case 1 (as-built) represents untreated material condition. In case 2 (800°C) the treatment temperature is just below the so-called β -transus temperature which means that no change in the

microstructure occurs. This condition was used to reduce residual stresses. In case 3 the samples were treated by "Hot Isostatic Pressure" (HIP). During the HIP process the samples are in a chamber filled with argon. Additionally, a temperature of 920°C and an isostatic pressure of 1000 bar are applied to the specimens. Case 4 (1050°C) is characterized by the exceeding of β -transus temperature and the associated formation of β -phase in titanium microstructure. Thus, after treatment at 1050°C the microstructure of Ti-6-4 includes both β -Ti and α -Ti. Further details about the microstructure are described and presented in [6].

FRACTURE MECHANICAL BEHAVIOR

Interactions between laser and material during the SLM process lead to evaporation and ejection of powder particles. This results in defects such as pores or inclusions. Additionally, due to the high cooling gradients internal stresses occur in the material. Therefore, investigations are necessary to analyze how these effects affect the fracture mechanical behavior of the materials.

The determination of the da/dN - ΔK -curves was conducted according to ASTM E 647-08 [7]. Investigations in terms of the near threshold behavior at low stress intensity factors were carried out at a frequency of 40 Hz. The upper range of the crack growth curves was recorded at a frequency of 10 Hz. All da/dN - ΔK -curves were determined at a constant R -ratio of 0.1 and at ambient conditions. The testing procedure was conducted by use of the INSTRON testing machine Electro-PulsTM E10000. During the crack propagation the on-line measuring system MATELECT DCPD (Direct Current Potential Drop) was used in order to obtain the data needed for analysis. The control and monitoring of the experimental procedure were carried out by the software ^{FAM}Control [8].

The experimental results are summarized in Figure 3 and Figure 4. At least for each test series a minimum of three tests were carried out. Additionally, data for the conventionally processed reference specimens were obtained from tests on samples removed of rolled sheet.

TABLE 1. Parameters of heat treatments for Ti-6-4.

Case	1 (as-built)	2 (800°C)	3 (HIP)	4 (1050°C)
Temperature [°C]	20	800	920 (1000 bar)	1050
Time [h]	-	2	2	2
Atmosphere	-	Argon	Argon	Vacuum

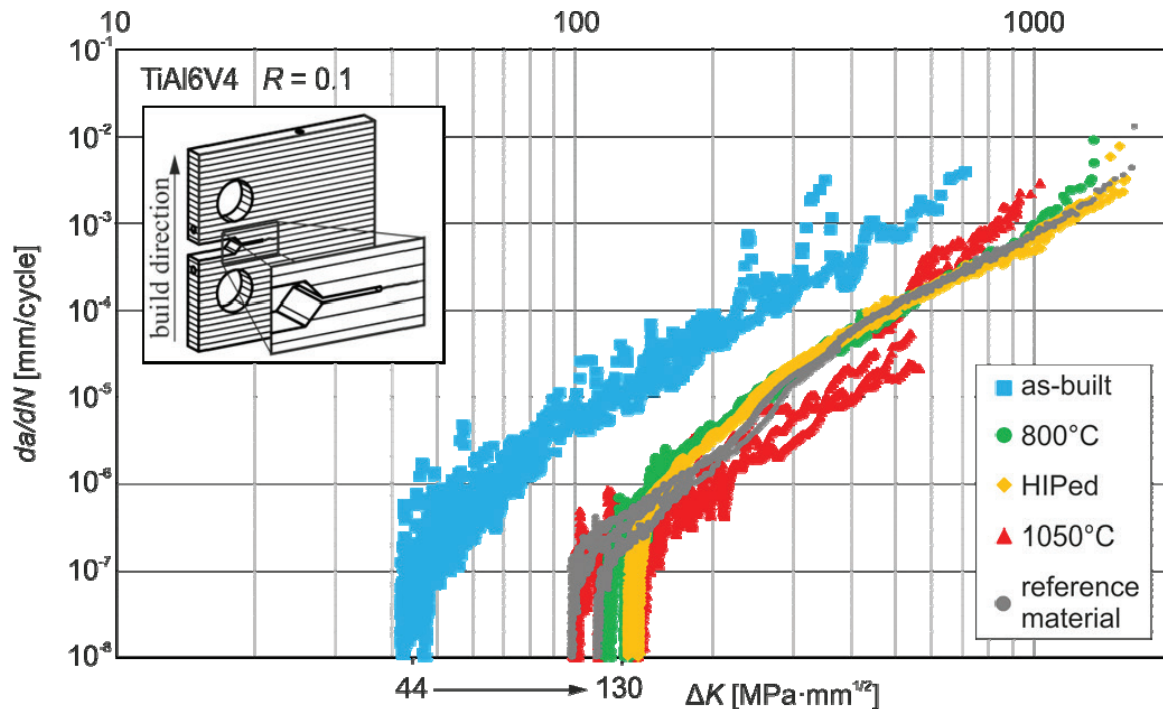


FIGURE 3. Results of crack growth tests for different conditions and perpendicular crack orientation to the build direction.

Moreover, a threshold value for crack growth of $125 \text{ MPa}\cdot\text{mm}^{1/2}$ was found in the literature [10]. The average threshold value for reference determined in these tests corresponds to a value of $105 \text{ MPa}\cdot\text{mm}^{1/2}$.

Figure 3 and Figure 4 show (amongst others) the test results for SLM components in the as-built state. In this condition low fracture mechanical values were determined. The average threshold value for the material built according to the direction as shown in Figure 3 is equal to $44 \text{ MPa}\cdot\text{mm}^{1/2}$ with a standard deviation of $\pm 2.2 \text{ MPa}\cdot\text{mm}^{1/2}$ ($\pm 5\%$). Test results given in Figure 4 for material manufactured corresponding to the crack orientation shown provide an average threshold value of $53 \text{ MPa}\cdot\text{mm}^{1/2} \pm 1.25 \text{ MPa}\cdot\text{mm}^{1/2}$ ($\pm 2\%$) in the as-built condition. The PARIS region of da/dN - ΔK -curves for as-built condition is significantly decreased compared to the reference material. Thus, in the untreated SLM components crack propagation and fracture by unstable crack growth occurs at much lower stress intensity factors of ΔK . Furthermore, the crack growth rates in as-built condition are subjected to a significantly higher scatter for a considered ΔK . The comparison of da/dN - ΔK -curves in as-built condition (c.f. Figure 3 and

Figure 4) shows that the average threshold value for build direction corresponding to parallel crack orientation is increased approximately by 20% compared to the threshold value for samples manufactured according to perpendicular crack orientation.

After a heat treatment at 800°C (c.f. Table 1) the crack growth curves were shifted to significantly more positive values of cyclic stress intensity ΔK (c.f. Figure 3 and Figure 4). Crack growth curves in Figure 3 show a good reproducibility. The average threshold corresponds to a value of $123 \text{ MPa}\cdot\text{mm}^{1/2} \pm 6.3 \text{ MPa}\cdot\text{mm}^{1/2}$ ($\pm 5\%$) and is similar to the threshold value of reference material. For crack orientation parallel to the built direction an average threshold value of $123 \text{ MPa}\cdot\text{mm}^{1/2}$ was determined, but with a slightly higher deviation of $\pm 15.8 \text{ MPa}\cdot\text{mm}^{1/2}$ ($\pm 13\%$), (c.f. Figure 4). The stable crack growth region is similar to the curves for tested reference material.

The results for HIP processed samples shown in Figure 3 provide a threshold value of $132 \pm 3.1 \text{ MPa}\cdot\text{mm}^{1/2}$ ($\pm 2\%$). This value is slightly increased compared to heat treatment at 800°C . The crack growth curves have no significant variations and have a good reproducibility

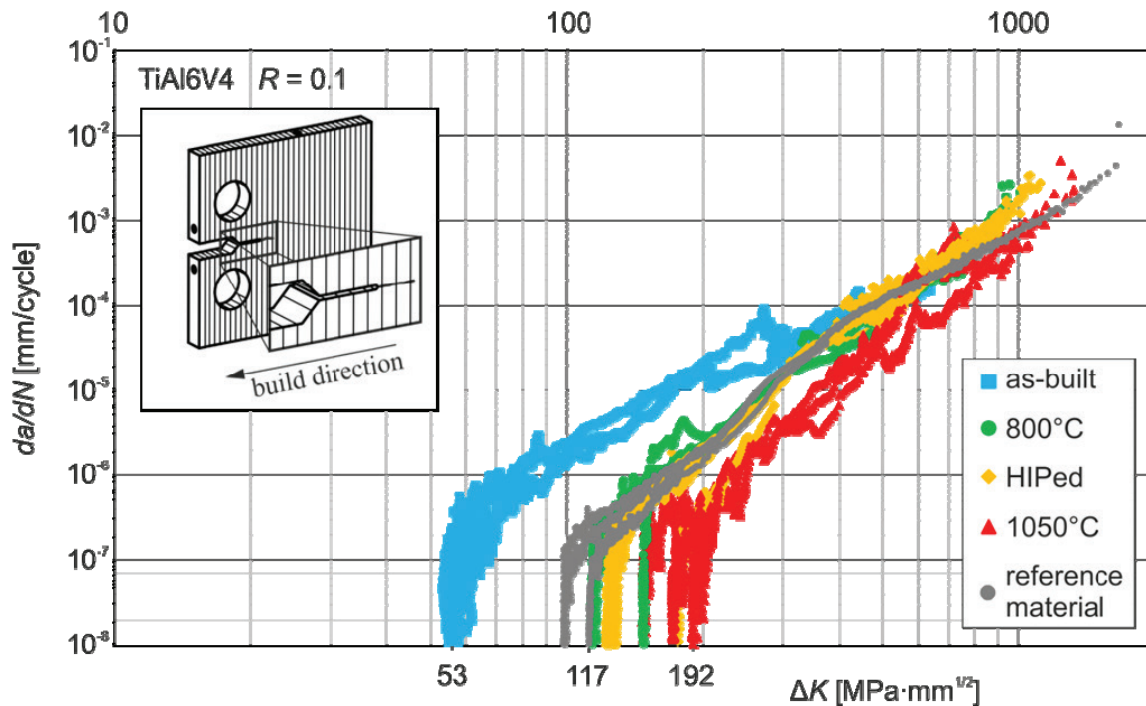


FIGURE 4. Results of crack growth tests for different conditions and parallel crack orientation to the build direction.

throughout the test series. In addition, they are very close to the data obtained for reference material.

The results for material treated at 1050°C provide the greatest fluctuations in the curve progression (compared to all test series with heat treatment). Both the average threshold value and the PARIS regime seems to have similar characteristics compared to the base material. Here, the threshold value is equal to $113 \text{ MPa}\cdot\text{mm}^{1/2} \pm 14.2 \text{ MPa}\cdot\text{mm}^{1/2}$ ($\pm 12\%$) and is slightly reduced compared to the threshold value of $125 \text{ MPa}\cdot\text{mm}^{1/2}$ (reference material from literature [9]) and higher than the threshold value found in experiments on reference material.

After treatment at 800°C, the initially occurring very high residual stresses can be reduced completely as represented in [5,6]. This step delivers the largest increase in fracture mechanical values (c.f. Figure 3 and Figure 4). However, the porosity remains unaffected. Thus, the internal stresses have a very large influence on the crack growth in SLM materials. Furthermore the HIP treatment reduces both the residual stresses and the pore size as represented in [6]. Also the resulting increase in fracture mechanical values compared to the

values for heat treatment at 800°C is minimal. Thus it must be noted that the pores have only a minor effect on the fatigue crack growth in SLM components while the residual stresses dominate the crack growth behavior.

SIMULATION OF LIFETIME

In this section, the effect of treatment is studied by simulating the crack growth of specimen to determine the lifetime. The software tool NASGRO [11] is used for the lifetime calculations. The relevant parameters for the lifetime calculation like threshold value have been taken from Figure 3.

In our simulation the CT sample is selected as an exemplary component to compare the different lifetimes for as-built and 800°C cases respectively Figure 5 shows the fitted curves for both fatigue crack growth values.

We have selected 5 constant force values as boundary conditions (shown in Figure 5) then calculated the 800°C to as-built ratio of the lifetime. As shown in Table 2 at a constant force of 380 N the ratio of the lifetime of heat treatment at 800°C to as-built is increased by a factor of 34.81, and for constant force of 800 N the ratio of the lifetime of heat treatment at

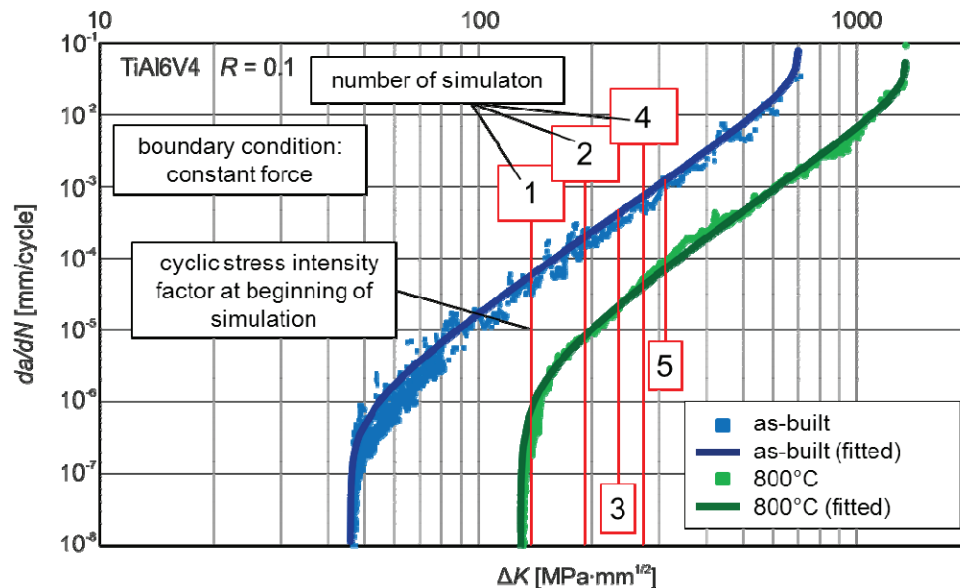


FIGURE 5. The experimental fatigue crack growth values and the fitted curves for as-built and 800°C.

800°C to as-built is increased by a factor of 16.82. From the simulation results we can see that as the constant force increases the lifetime ratio decreases.

TABLE 2. Lifetime ratio for different constant force values

Simulation number	Constant force	Ratio of lifetime
1	380N	34,81
2	500N	19,27
3	600N	17,41
4	700N	16,81
5	800N	16,82

CONCLUSION

The conducted studies show that residual stresses which occur in the titanium alloy have a very high influence on the crack growth. When a crack is present in a SLM component, it should be treated at 800°C in order to achieve a significant improvement of the fracture mechanical material behavior. The resulting residual life of this component can be increased as shown by the lifetime simulation up to a factor of 34.

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SQAURENESS MEASUREMENT OF A COORDINATE MEASURING MACHINE USING A LASER INTERFEROMETER SYSTEM

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INTRODUCTION

Test artifacts or benchmarking parts which are made by an additive manufacturing (AM) machine are usually used to evaluate its performance [1]. Coordinate measuring machines (CMMs) is suitable to measure the dimension tolerance of a test artifact due to its flexible measurement capabilities and a high resolution. The measuring performance of a CMM is significantly influenced by the positioning accuracy. Geometric error is known as the main cause of the positioning accuracy of a CMM, especially, the squareness between driving axes.

According to the ISO10360-2 [2], the evaluation for positioning accuracy of CMMs is performed by using a set of five length accurate gauges. Another method for evaluation of geometric error of CMM was presented by Knapp [3] where in the circular test using a circular master. Recently, double ball-bar is widely used instead the circular master for circular test. Laser interferometer system is also applied to evaluate the positioning accuracy of CMMs due to its large measurable range and high-resolution [4].

In this study, a developed method for measuring the squareness of a CMM using laser interferometer is presented. Firstly, the algorithm proposed by Lee et al. [5] was applied to improve the accuracy of the measurement system where in the measurement error was mathematically eliminated based on the measurement offset and measured angular error for full travel range measurement. Secondly, four diagonal test data was utilized to measure the squareness using laser interferometer without optical square. The verified experiments were performed using the XL-80 laser interferometer system (Renishaw plc, UK) and were conducted on XY-plane of the CMM.

SQUARENESS MEASUREMENT USING A LASER INTERFEROMETER SYSTEM WITH AN OPTICAL SQUARE

Laser interferometer with an optical square is commonly used for squareness measurement. However, it has the accuracy problems due to the measurement error (ME) caused by measurement offset (MO) from the origin of reference coordinate system (RCS) to the initial position of a interferometer as shown Figure 1. Where, a_{xx} is the MO in X-direction of X-axis measurement. The MOs including Abbe's offset and axial offset are inevitable due to the optical square installation. Moreover, the measurable range is restricted due to the installation of optical components of the system. Lee et al. proposed an algorithm to solve this problem using mathematical approach.

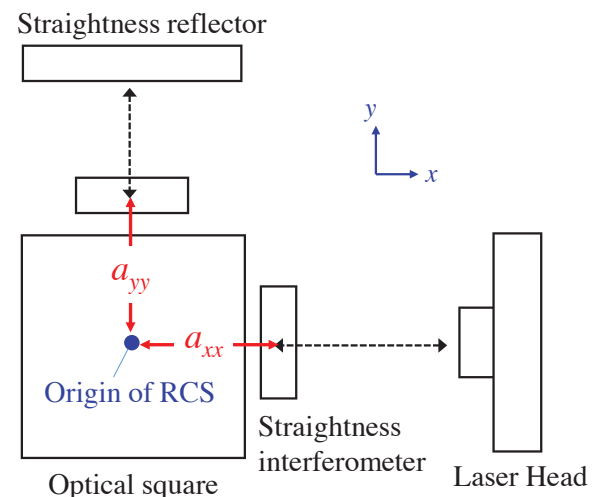


FIGURE 1. MOs (a_{yy} , a_{xx}) in squareness measurement using laser interferometer with an optical square

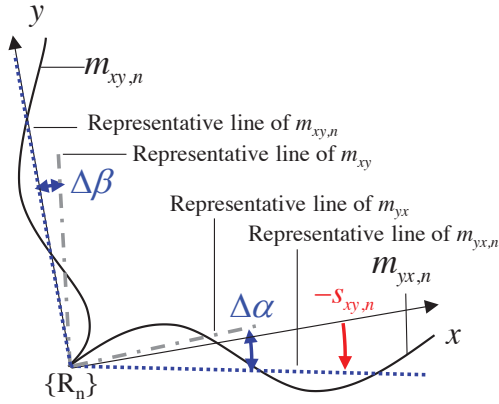


FIGURE 5. Angular differences of between partial and full travel range straightness representative lines and squareness for full travel range

The full travel range squareness is simply estimated by using the angle differences $\Delta\alpha$, $\Delta\beta$ of straightness representative lines of two axes as shown Figure 5. The angular difference $\Delta\alpha$ is obtained by calculating the angle (α , α_n) of partial and full travel range representative lines of X-axis straightness in the MCS of the full travel range straightness data as given by Eq. (3). Similarly, the angular difference $\Delta\beta$ for Y-axis is calculated as given by Eq. (4).

$$\Delta\alpha = \alpha_n - \alpha \quad (3)$$

$$\Delta\beta = \beta_n - \beta \quad (4)$$

Finally, the squareness $s_{xy,n}$ for the full travel range is obtained as

$$s_{xy,n} = s_{xy} - (\Delta\alpha + \Delta\beta) \quad (5)$$

SQUARENESS MEASUREMENT WITH FOUR DIAGONAL TEST USING LASER INTERFEROMETER

In this section, squareness measurement technique without using optical square is presented. This technique is developed to measure the squareness of the machine where the installation of the optical square is limited due to machine structure. With four diagonal tests, straightness and angular error, the squareness is calculated without inverse kinematic analysis.

Volumetric Error Based on Machine Structural Configuration

In general, a machine structural configuration is determined from combination of three linear axes. The volumetric error of a CMM is defined

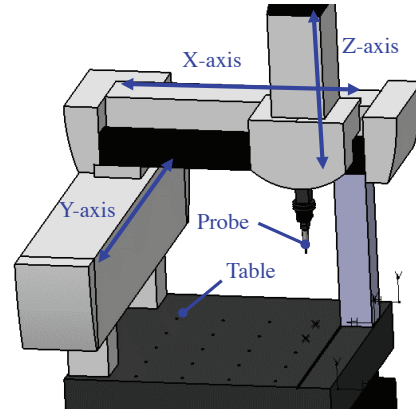


FIGURE 6. Structural configuration of the CMM

as the deviation between design position and actual position of contact point of probe tip. In ISO 10360-2, the volumetric error of a CMM is classified as the volumetric length measuring error and volumetric probing error.

In this study, the volumetric probing error is not considered because squareness relates to driving axes only. Therefore, the origin of reference coordinate system is set at the probe center. In case structural configuration is Reference – Y – X – Z – Probe as shown Figure 6, the position of PC with respect to RCS is expressed as Eq. (6).

$$\tau_R^P = \tau_R^Y \tau_Y^X \tau_X^Z \tau_Z^P = \begin{bmatrix} \text{ROT} & \text{TRS} \\ \mathbf{0} & \mathbf{1} \end{bmatrix} \quad (6)$$

where, τ_A^B is the transformation matrix of B coordinate system with respect to A coordinate system. **ROT** and **TRS** is respectively the rotation matrix and translation vector of the probe center with respect to the RCS.

The volumetric error vector $\Delta\mathbf{W}$ is obtained by eliminating the machine command vector $\mathbf{T}$ from the **TRS** as followed:

$$\Delta\mathbf{W} = \text{TRS} - \mathbf{T} \quad (7)$$

Components of the volumetric error is given as

$$\begin{aligned} \Delta x &= \delta_{xx} + \delta_{xy} + \delta_{xz} + \varepsilon_{yx}z + \varepsilon_{yy}z + s_{zx}z \\ \Delta y &= \delta_{yx} + \delta_{yy} + \delta_{yz} + \varepsilon_{zy}x + s_{xy}x \\ &\quad - \varepsilon_{xz}z - \varepsilon_{xy}z - s_{yz}z \\ \Delta z &= \delta_{zx} + \delta_{zy} + \delta_{zz} - \varepsilon_{yy}x - s_{zx}x \end{aligned} \quad (8)$$

where, δ_{ij} and ε_{ij} are position error and angular error in i -direction of j -axis, respectively. And x , y and z are machine command of X-, Y- and Z-axis, respectively.

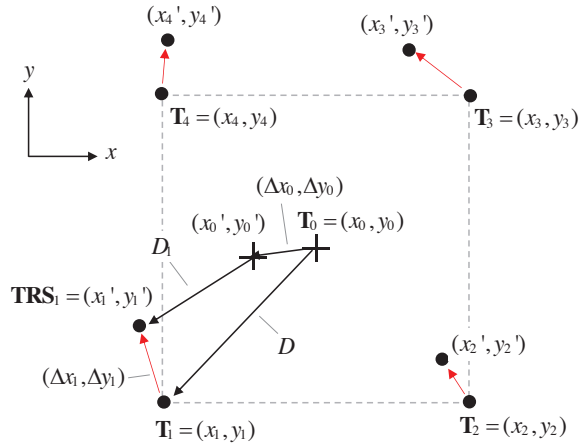


FIGURE 7. Diagonal tests in the XY-plane

Squareness Measurement using the Four Diagonal Test

The data of four diagonal ($-3\pi/4$, $-\pi/4$, $\pi/4$, $3\pi/4$) tests measured by laser interferometer and the straightness error and angular error are applied to calculate the squareness. First, the diagonal test on $-3\pi/4$ with respect to center position T_0 of measurement is performed as shown Figure 7. The measurement D_1 including the diagonal length D as well as diagonal error E_{D1} is given as

$$D_1 = D + E_{D1} \quad (9)$$

$$D + E_{D1} = \sqrt{[(x_1 + \Delta x_1 - x_0 - \Delta x_0) + (y_1 + \Delta y_1 - y_0 - \Delta y_0)]^2} \quad (10)$$

Taking the square of both side of Eq. (10) and eliminating the second order terms, the diagonal error is calculated as given by Eq. (11). This equation agrees with the double ball-bar equation.

$$E_{D1} = \{(x_1 - x_0)(\Delta x_1 - \Delta x_0) + (y_1 - y_0)(\Delta y_1 - \Delta y_0)\} / D \quad (11)$$

Similarly, diagonal errors E_{D2} , E_{D3} , E_{D4} can be obtained.

Followed equation is proposed for estimating the squareness with diagonal test data.

$$C = \sum_{n=1}^4 (-1)^n E_{Dn} / 2D \quad (12)$$

Substituting Eq. (8) into Eq. (11), the diagonal error is

$$E_{Dn} = \{(x_n - x_0)(\delta_{xx,n} + \delta_{xy,n} - \delta_{xx,0} - \delta_{xy,0}) + (y_n - y_0)(\delta_{yy,n} + \delta_{yx,n} + \varepsilon_{zy,n}x_n + s_{xy}x_n - \delta_{yy,0} - \delta_{yx,0} - \varepsilon_{zy,n}x_0 - s_{xy}x_0)\} / D \quad n=1,2,3,4 \quad (13)$$

Linear displacement error δ_{xx} , δ_{yy} not affects to the C value according to Equation (12) substituted Equation (13). Let C' is the result of Eq. (12) using two straightness error δ_{xx} , δ_{yy} and angular error ε_{zy} without squareness. Then the squareness can be calculated as

$$s_{xy} = \frac{C - C'}{2D} \quad (14)$$

EXPERIMENT

Experiments were performed on the XY-plane of the CMM as shown Figure (8) and (9) respectively. The partial-range and full-travel-range are 200 mm $\times$ 200 mm and 400 mm $\times$ 400 mm, respectively.

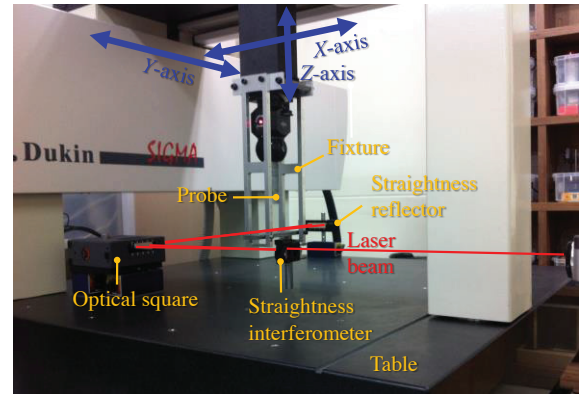


FIGURE 8. Squareness measurement using laser interferometer with optical square



FIGURE 9. Diagonal test setup

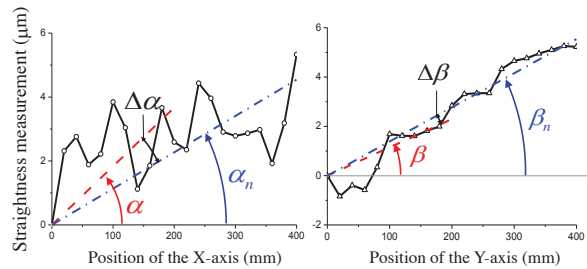


FIGURE 10. Angular differences of representative lines between the partial range and full-travel range straightness (with optical square) (a) for X-axis (b) Y-axis

TABLE 1. Squareness measurement with optical square and squareness estimation for the full-travel-range

Range(mm×mm)	200×200	400×400
Squareness (μm/m)	33.6	28.3

TABLE 2. Measurement points of the diagonal tests

	x	y
T ₁	58.579	58.579
T ₂	341.421	58.579
T ₃	341.421	341.421
T ₄	58.579	341.421

TABLE 3. Squareness measurement with optical square and squareness estimation for the full-travel range

Measurement technique	with optical square	with the diagonal test data	Discrepancy
Squareness (μm/m)	28.3	33.2	4.9

The partial-range and full-travel-range are 200 mm × 200 mm and 400 mm × 400 mm, respectively. The angular differences of representative lines are shown in Figure 10. The results are shown in Table 1. The difference between the partial range and the full travel range squareness is 5.3 μm/m. Although the difference is relatively small, it can significantly affect the performance of the CMM if a high measuring accuracy is required.

Measurement points for four diagonal tests are presented in Table 2. The result of squareness

calculation is compared to the squareness measured with optical square and a discrepancy of 4.9 μm/m was observed.

CONCLUSION

In this study, the squareness measurement techniques using laser interferometer with and without optical square have been presented. In the first techniques the measurement errors are eliminated and the squareness is estimated for full travel range. The second technique utilizes the data of four diagonal tests, straightness errors and angular errors to estimate the squareness of the CMM without using optical square. These techniques are suggested on the purpose of overcoming the problem of optical square installation due to limitation of machine structure. More importantly, these techniques improve the dimension measured accuracy of the test artifacts of AM machines using CMM.

ACKNOWLEDGEMENTS

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Generative tool manufacturing for the replication of micro-optical components

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INSTRUCTION

The manufacturing of large quantities of polymeric optical and micro-optical components becomes more and more important regarding to industrial applications as MEMS devices, customer electronics or micro imaging systems. In particular, the manufacturing of polymeric micro-optics by micro injection molding requires further improvement concerning the whole process chain in order to achieve the needed process capability for high-quality mass production.

Major aspects of current development are mold technology and the associated manufacturing technologies. Especially dimensional accuracy of micro features, surface quality and surface temperature homogeneity are key influencing parameters on replication results [1].

In this paper, an approach for the additive manufacturing of micro-injection molding tools is presented that meets the requirements for a high precision replication of features as microlenses or optical gratings. Simultaneously the tool concept improves the temperature constancy of the mold surface in the area of the

micro features and along with this, dimensional accuracy and shape stability of the replicated plastic parts.

MICRO INJECTION MOLDING OF MICROLENSES

Injection molding of microlenses imposes high demands on the injection molding process and on the machine tool as well as the mold technology. The relevant parameters for the qualification of polymer microlenses are substantially equivalent to those used in traditional refractive optics. Surface roughness, shape and positional tolerances, refractive index, molecular orientation and injection molding process induced deviations are key influencing factors on component quality and optical functionality.

For a repatriation of these quality indicating parameters on manufacturing boundary conditions, a reference structure was designed and manufactured (FIGURE 1).

Starting from a FEM simulation of the injection molding process with the Software Autodesk Moldflow Insight and subsequently transferring

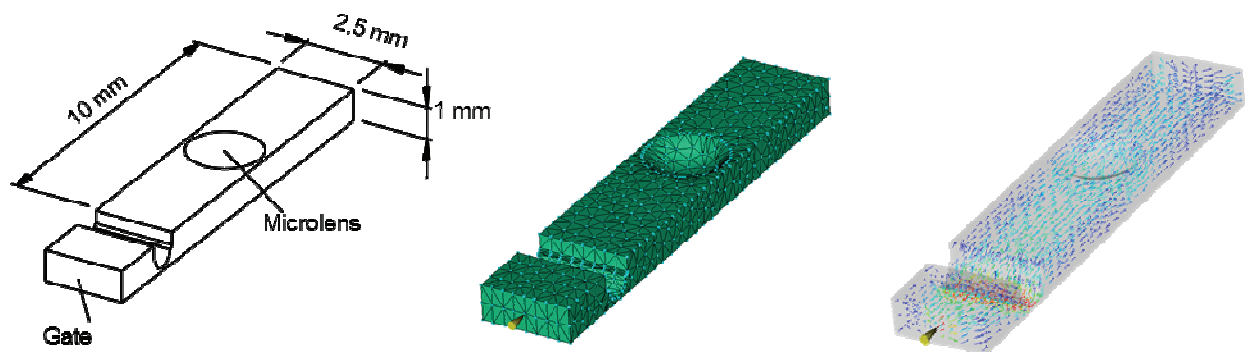


FIGURE 1. Mold insert for the replication of a single micro-lens, resultant mesh for the FE-based analysis of the injection molding process and the velocity vector field during mold filling process

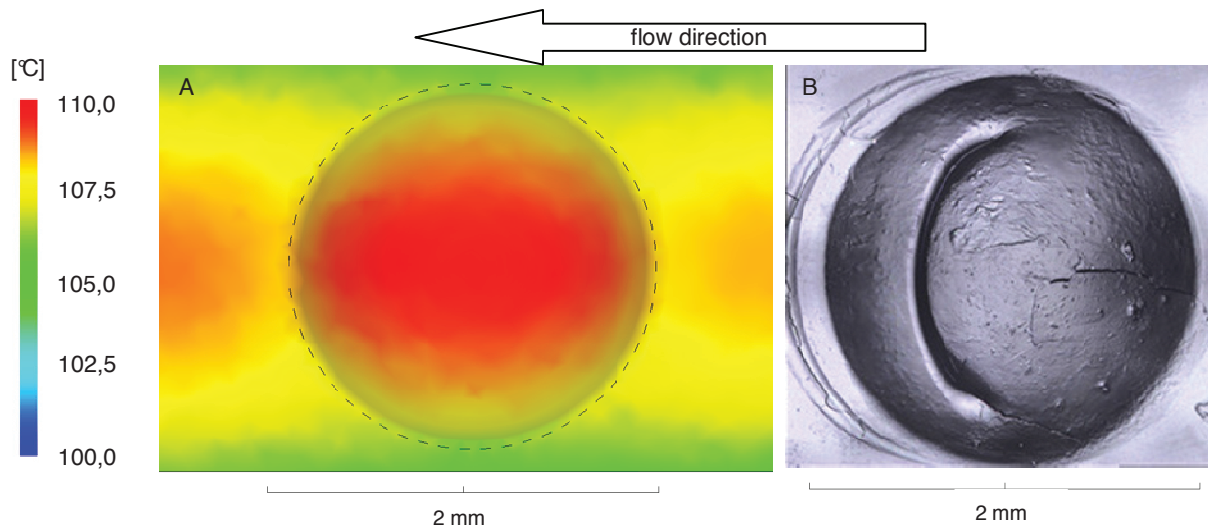


FIGURE 2. Temperature distributions on the mold surface with conventional, channel based mold tempering and replicated micro-lens

to and reproducing these results with a Battenfeld Microsystem 50 injection molding machine tool, mold surface temperature was identified as a boundary condition significantly influencing the optical functionality.

The injection molding tool used for the replication of the samples was conventionally tempered with fluidic, water based temperature control by 8 mm drill holes with a distance of 25 mm to the mold surface. Resulting mold surface temperatures are presented in Figure 2A. According to the results of temperature measurement, the shape of the lens corresponds to the injection molding simulation (Figure 2B). In particular, inhomogeneities in the peripheral zones of the lens surface show a strong impact on lens replication quality.

INFLUENCE OF MOLD SURFACE TEMPERATURE ON SHAPE AND POSITIONAL TOLERANCES AND SURFACE FINISH

The mold surface temperature has several independent impacts on mold-filling process and on the replication results.

In this context, the formation of a creeping, solidified layer in contact with the mold surface provides the basis for the filling of micro-cavities. The homogeneity of this layer affects directly the close-to-wall micro flows. Every inhomogeneity on the mold surface temperature leads to traverse flows concerning the main flow direction and in this regard to surface defects (Figure 2).

Another aspect of mold temperature control concerns the cooling of the plasticized material following the injection process. The material solidifies starting from close-to-wall areas to the core of the injection molded part. Because of the correlation between heat-transfer capacity of the tool structure and surface temperature homogeneity, a conclusion can be drawn to

part into the mold during cooling cycle. Inhomogeneous heat dissipation from the plastic part leads in this context to a deformation, especially of the micro-optical elements of the plastic part and a failure to perform the optical purpose.

IMPROVEMENT OF HOMOGENEITY OF SURFACE TEMPERATURE

Generative manufacturing of molds or mold inserts offers the possibility of increasing the temperature control capabilities, temperature homogeneity of the mold surface and along with this, a significantly improved quality of the injection molded lenses.

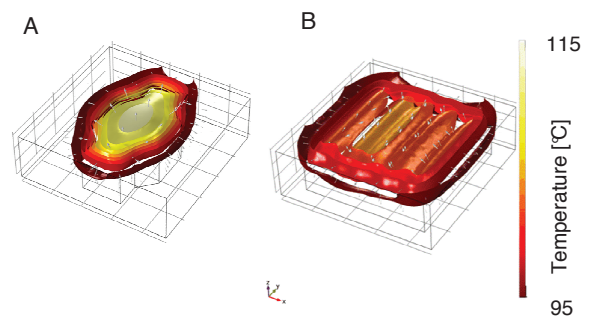


FIGURE 3. Isothermal curves of a FE-based mold temperature analysis, additive manufactured tempering element (A), conventional channel based mold tempering (B)

As shown in figure 3, a mold insert with a conformal, close-to-surface tempering channel results in a more homogenous temperature field whereas channel based tempering results in an inhomogeneous temperature distribution.

In particular, equally wall thickness between channel and mold surface or micro-cavities that are completely enclosed by tempering elements induce the increase of quality.

SELECTIVE LASER MELTING FOR THE MANUFACTURING OF ULTRA-PRECISION MOLD INSERTS

Selective Laser Melting (SLM) is an additive manufacturing (AM) technique for the layer-by-layer replication of components made from metal materials. Usable materials include aluminum, stainless steel, titanium alloys or nickel-based alloys in the form of metal powders with distinct diameters between $10\text{ }\mu\text{m} \leq d_p \leq 75\text{ }\mu\text{m}$. These powders are melted by laser beam to produce components, whose mechanical properties are equivalent to conventionally machined parts.

For the replication, the CAD model is sliced into layers with a thickness of $30\text{ }\mu\text{m} \leq s \leq 50\text{ }\mu\text{m}$ and hatched with a material specific pattern. The SLM process can be divided into three sequential steps. During the moving step, the building platform is lowered by one layer-thickness. This is followed by the coating step whereas one layer of metal powder is applied. During final step, the current layer geometry is fused by laser melting.

In comparison with conventional machining methods the surface quality of SLM produced components is characterized by a high surface roughness. Currently obtained mean roughnesses are in range of $40\text{ }\mu\text{m} \leq R_z \leq 50\text{ }\mu\text{m}$. Due to achievable surface qualities, the finishing process of SLM components is still challenging with regard to post-processing manufacturing technologies.

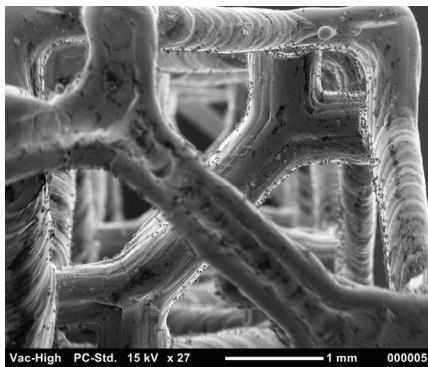


FIGURE 4. Generative manufactured lattice structures in the tempering channels for increased heat exchange ration

By the use of SLM, injection molding tools can be generated. This offers the opportunity to integrate an inbound, near-to-surface and highly-complex tempering channel system. In addition, lattice structures can be integrated

(Figure 4) to increase the ratio of heat exchange between tempering fluid and mold material by enlargement of the specific surface and increasing the Reynolds number in the fluidic channel system.

MANUFACTURING RELATED LIMITATIONS IN GENERATIVE MANUFACTURING OF IN-MOLD CAVITIES

One of the main differences between additive and conventional manufacturing is the use of support structures. These structures are required for the derivation of the laser induced energy and in this context, for the prevention of thermal induced stress or deformation.

However, in particular for the use of SLM for the manufacturing of molds for micro injection molding, process related limitations are present.

Due to the layer-by-layer manufacturing process, a wall thickness below layer thickness is currently impossible. Inboard structures are replicated at the surface of the manufactured component and hence, a post-processing by ultra-precision machining is impracticable due to geometrical errors.

Because of the process-related layer thickness between $30\text{ }\mu\text{m} \leq s \leq 50\text{ }\mu\text{m}$, the fluidic structures can as well be manufactured with a minimal distance to mold surface of $50\text{ }\mu\text{m}$.

REQUIREMENTS FOR ADDITIVE MANUFACTURING

To increase the homogeneity of the mold surface temperature of micro-optical components, a modular tool insert was manufactured through AM. Therefore, the geometry, the material and a way to proof the tool quality needed to be chosen. The main aims for the geometry were the close-contouring of the cavity with the cooling channel and a laminar flow. The criteria for the choice of material were thermal conductivity, availability and the pricing. AlSi12 provides one of the highest thermal conductivities ($120\text{-}190\text{ [W/(m}^{\circ}\text{K)]}$) and reasonable expenses (60 [€/kg]).

In addition, the manufacturing of micro-optical structures can be done by ultra-precision milling/turning without having to perform complex coating steps.

ADDITIVE MANUFACTURED COMPONENT QUALITY

Apart from the examination of the used powders quality, an analysis of the tensile strength, hardness, density and roughness of the generated component was necessary. Each new

developed or used additive material needs to be examined, regarding to the mentioned properties by using the VDI 3405.

The investigations of the AlSi12 showed a tensile strength between 340 MPa and 400 MPa, The yield strength was measured as 175 MPa up to 215 MPa. The elongation at break was in the range of 1 % up to 1,9 %. The average hardness and the density were measured with 100 HV10 and 98,2 %.

EFFECTS FROM THERMAL TREATMENT OF THE ADDITIVE MATERIAL

Many materials can be processed by heat treatment, to change their mechanical properties selectively. In the case of the used AlSi12, the untreated condition was compared with a solution annealed (6h with 525°C).

Differences occurred in all measured properties. However, only the elongation at break was increasing. Therefore no heat treatment was used for the modular tool inserts.

CONCLUSION

Modular tool inserts were successfully manufactured and their effects on injection molding results were investigated. Most of the mechanical properties of the used AlSi12 were above the average for aluminum cast. Therefore an optimized tensile strength, yield strength and hardness could be achieved. Only the elongation at break was below average.

A Simulation of additive and conventionally produced tool inserts showed the possibility to increase the ratio of the heat exchange through additive made tool inserts. The experimental validation of these results has not been confirmed yet. Nevertheless, first experiments of injection molding show promising results.

The detected roughness of additive manufactured surfaces is higher than the roughness of surfaces treated with conventional manufacturing techniques.

Therefore, high-precision milling with cemented carbide end-mills and ultra-precision milling with single-crystal diamond end mills were used as post processing steps for the generation of micro-optical structures.

FUTURE WORK

An aim for the future is the manufacturing of micro injection molds with AM, which are capable of processing components faster and with a higher quality.

For SLM the qualifying and use of a bigger material variety e.g. AlSi10Mg is required. The

mechanical properties of this material can be optimized through heat treatment, because its hypoeutectic.

Therefore, high-precision milling with cemented carbide end-mills and ultra-precision milling with single-crystal diamond end mills

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Control of Microstructural Evolution in Powder Bed Fusion Additive Manufacturing in Relation to Functional Properties of Metals

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INTRODUCTION

To date, Additive Manufacturing (AM) has been adopted for low-tech consumer markets and industrial prototyping. However, AM cannot meet the stringent requirements for high tech / high precision / high complexity manufacturing. This area of research is extremely interesting, as the market for AM equipment, materials and service is expected to grow to \$ 5 billion by 2020.

With the advancement of additive manufacturing activities in the area of Powder Bed Fusion (PBF), it has become clear that a more thorough understanding of the process parameters that influence the material's functional properties is a needed. This is especially true when considering additive manufacturing techniques applied to the high tech and aerospace markets.

The following methodology has been employed to approach the improvement of this technology:

- Measure to observe: powder bed inspection via infrared or optical imaging, measurement of composition or structure.
- Model to understand: thermo-mechanical/flow modelling of powder bed / laser fusion process, predictive modelling to compensate for imperfections, heat unbalance, and microstructural development.
- Act to close the loop (controlled-feedback): novel control strategies, high-speed and accurate powder deposition, multiple laser strategies, and write-strategies to improve product performance

In this work, numerical simulations of microstructure development as a function of melt pool solidification a thermal history have been investigated. Furthermore, initial experiments to directly measure the change in microstructure as

it undergoes a laser melting process will be carried out. Finally, the path forward is described.

METHODOLOGY

The aim of this study is to develop more advanced modelling techniques. To achieve this goal a framework of multi-scale modeling and thermodynamical modeling will be developed, see Figure 1. The models will be validated with accompanying experiments designed specifically for material parameters in the models.

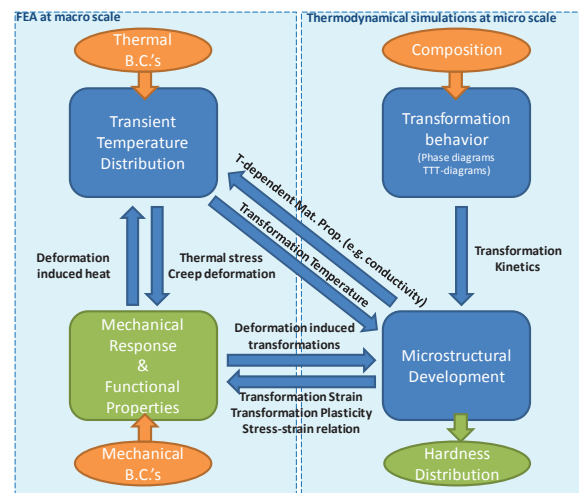


FIGURE 1. Framework for multi-scale & multi-physics simulation of SLM.

Material Aspects

In AM when applying layer after layer with the Selective Laser Melting (SLM) process, the stress build up within the printed part will be significant. As a consequence, either during the printing process or when it is released from its base, the part will warp or deform. A process that is quite similar to SLM is a *welding* process or even more similar *surface welding*. It is well

known that in these processes the material properties (i.e. hardness, yield strength, tensile strength and ductility) in the direct vicinity of the weld are distinctly different from the base material. The welded zone is divided into three zones, see Figure 2:

(i) the *weld pool* and on the transition from liquid-to-solid (i.e. the *fusion line*), (ii) the Heat Affected Zone (HAZ) and further outward where the heat did not have a chance to affect the original microstructure of the *base material* (BM). In these zones the material properties will distinctly differ from the properties of the base material. The underlying phenomena that cause these changes are not so much compositional changes but microstructural changes, phase transformations and its accompanying internal stress development.

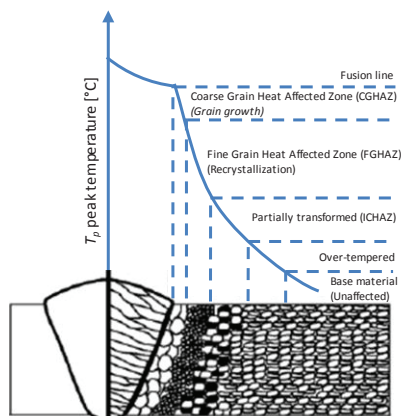


FIGURE 2. Schematic cross-section of a welded joint with a weld pool, fusion line, heat affected zone and base material.

Building a part will require many passes close to each other. Each pass will affect the thermal history of neighboring points. So when monitoring one particular location over time will result in a complex temperature profile.

Geometry and precision are important requirements but the functional properties like yield strength, tensile strength, ductility hardness, fatigue resistance, corrosion resistance, heat conduction, etcetera gain more and more interest. So when trying to model the deformation with the use of a classical Finite Element approach a thermo-mechanical would suffice. Though this kind of modelling is more qualitative than quantitative, calibration of the end result will be necessary. When doing basic thermo-mechanical modelling, the total strain

can be defined as the sum of elastic strain and thermal strain:

$$\varepsilon_{tot} = \varepsilon_e + \varepsilon_{th}$$

With ε_{tot} the total strain, ε_e the elastic strain and ε_{th} the thermal strain. Plastic strain can easily be added to account for stress redistributions when local stresses exceed the yield stress. When trying to increase the predictive power of the thermo-mechanical modelling, more of the underlying phenomena have to be taken into account. But this is not the only reason to incorporate microstructural phenomena. Including microstructural evolution is also required if functional properties need to be predicted. For this the strain formulation can be augmented:

$$\varepsilon_{tot} = \varepsilon_e + \varepsilon_{pl} + \varepsilon_{th} + \varepsilon_{ve} + \varepsilon_{cr} + \varepsilon_{tr} + \varepsilon_{tp}$$

With ε_{pl} the plastic strain, ε_{ve} the visco-elastic strain, ε_{cr} the creep strain, ε_{tr} the strain from phase transformations and ε_{tp} phase transformation induced plastic strain.

MODELING APPROACH

We are developing a multi-scale/multi-physics modelling framework. At the highest level FE-models will be used to simulate the SLM-process, providing the underlying models with accurate temperature distributions and the macroscopic strains (ε_{el} , ε_{pl} , ε_{ve} and ε_{pl}). At the microstructural level both both FE and Thermo-dynamical models will be adopted to provide the additional strains (ε_{tr} and ε_{tp}) that describe the microstructural changes and hence affect the material's functional properties.

MICROSTRUCTURAL/THERMO-DYNAMICAL MODELING

For the thermo-dynamical modeling a combination of Monte Carlo (MC), Phase Field (PF) and Cellular Automaton (CA) is used and is also known as Q-state Cellular Potts Model (CPM) which originates from the two-state Cellular Automaton Model, the so-called Ising Model. This CPM model will be used to keep track of the grain growth in the HAZ.

For the phase transitions and the accompanying volumetric strain, TTT-diagrams and dilatometric diagrams will be used, e.g. the one given in Figure 3. The changes in volume are such that they exceed the 0.2% yield strain easily.

Therefore the microstructure will be subject to plastic deformation and internal stresses develop when these phase transitions occur. Finite element simulations will be used to quantify these contributions.

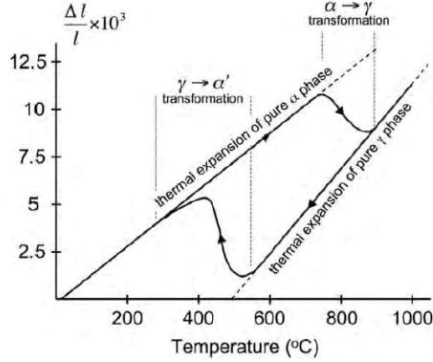


FIGURE 3. Example of a dilatometric diagram show the significant volume changes when between α and γ phase [1].

Q-STATE CELLULAR POTTS MODEL

For modeling the grain growth the Q-state Cellular Potts Model is chosen [2], [3], [4]. In this model a domain is defined wherein each grid point is given a particular state $Q_i \in [1, Q_{max}]$ which represents its local crystallographic lattice orientation. In this way when neighboring points have the same state, they form an actual crystal. From the domain a point is chosen at random and for this point the state is compared with its direct neighbors and the total free energy is determined by:

$$G = -J_{gb} \sum_{nn} (\delta Q_i Q_j - 1)$$

With J_{gb} the interfacial energy for the grain boundaries and $\delta Q_i Q_j$ the Kronecker delta between the sampled point with state Q_i and its direct neighbors with states Q_j . After calculating the initial free energy G_1 , the state Q_i of the sampled point i is at random changed to the state of one of its neighbors and again the free energy G_2 is calculated. If the free energy is lower ($\Delta G = G_2 - G_1 \leq 0$) the state change is accepted. If the free energy increases there will still be a small chance of accepting this state change according to:

$$P(\Delta G) = \begin{cases} 1 & \Delta G \leq 0 \\ \exp(-\alpha \Delta G) & \Delta G > 0 \end{cases}$$

In which α is the temperature factor. The model can easily be expanded to account for anisotropic grain growth, second phase particles and including viscous (molten) phase and gaseous phase (for sintering purposes). The initial microstructure can be generated by computer or by e.g. an EBSD (Electron Back Scattered Diffraction) image of the microstructure. In Figure 4 a random state field is generated and over time the polycrystalline microstructure develops by grain growth.

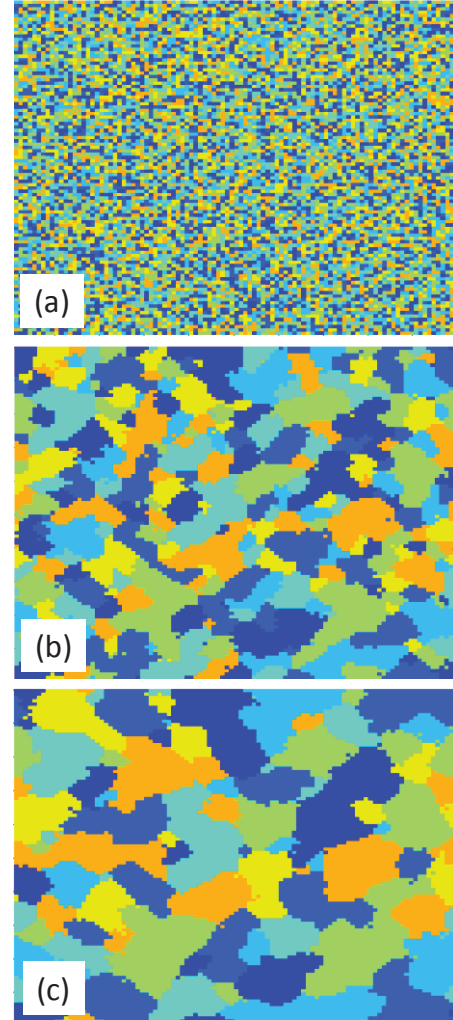


FIGURE 4. Grain growth simulation from (a) random initial state, (b) growing grains and (c) annihilating smaller grains in favor of larger ones.

CONCLUSIONS AND FORWARD PLANNING

In this work, theoretical calculations of microstructure development as a function of melt pool solidification and thermal history have been

investigated. Furthermore, initial experiments to directly measure the change in microstructure as it undergoes a laser based melting process will be carried out in order to validate the theoretical findings.

Formalizing the link between understanding the microstructural development and utilizing the results in practice to obtain functional parts will greatly enhance the impact of additive manufacturing in the high tech and aerospace markets.

Future work will progress to make the link of measuring to observe, modelling to understand, and acting to close the loop.

QUESTIONS

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DESIGN RULES FOR ADDITIVE MANUFACTURING: DESIGNING FOR THE PROCESS

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INTRODUCTION

The objective of this paper is to elaborate on designing for the process of 3D metal printing. These rules, when adhered to, will allow for greater part accuracy, less failed or incorrect builds, & more efficient use of the metal powder & machine time. Also, the necessary secondary processing will be greatly reduced. The sights are set ahead so that, in time, every part can be pulled off the machine in its final production ready form. While machine resolution and technology is not perfect yet, we know that when designing from the beginning, using these rules will create high resolution, 100% dense, and fully functional components.

DESIGN RULES FOR DMLS

Usable Materials for the DMLS Process

Here at Linear, we use an array of metals that have slightly different design tolerances. If the material our customers want to use is not available, usually the part can be substituted with one of our readily available materials that have similar properties.

Aluminum is ideal for applications that require a combination of good thermal properties & low weight. So with those attributes in mind, aluminum components can be built with thinner walls than average.

Cobalt Chrome has excellent mechanical properties so it is commonly used in biomedical applications such as dental & medical implants. This does not intrinsically mean that the material is used for freeform geometries but it does become a good candidate for such implants due to biocompatibility.

Inconel is widely used for high temperature applications such as gas turbine, instrumentation, and power & process industry parts.

Maraging Steel is easily heat treatable so it is used for parts that require excellent hardness & strength.

Stainless Steel is used over wide temperature ranges and used across many industries

including food processing, medical, aerospace, and oil & gas.

Titanium is much like Cobalt Chrome in its usage, yet it provides a low specific weight, has very different design & build parameters due to its inherent chemical difference.

While each of these materials are quite different in their makeup and application, there are general design basics that will help guarantee a successful build. These tolerances and guidelines help push the boundaries of what the technology can actually do while still producing viable parts.

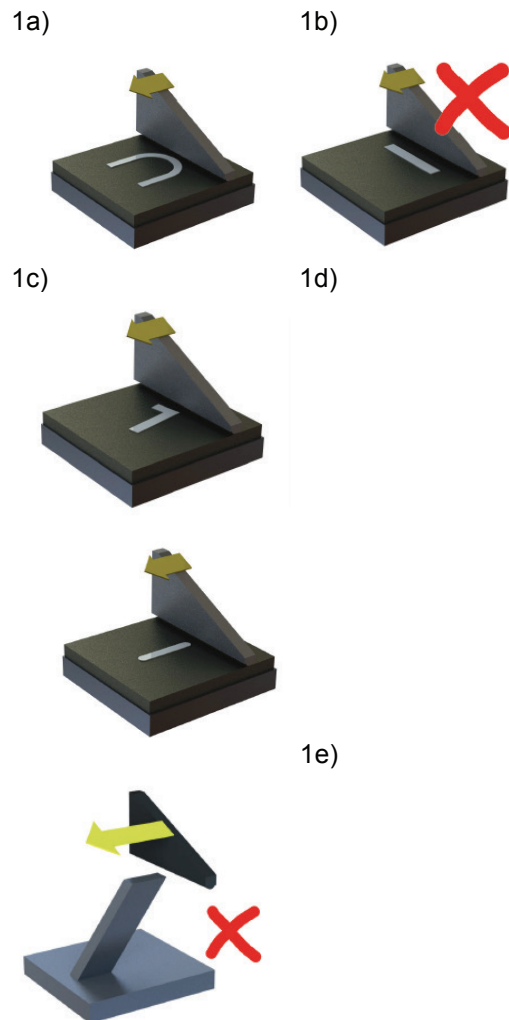
Each part is built in essentially the same way. A layer of metal powder .02-.05mm thin is spread across a build platform via a recoater blade. Then, a laser melts the cross section of the part at that layer bonding it to the previous layer. The platform then lowers allowing the powder to be spread again to repeat the process. Now, herein lay the impetus for the rules to take into account when designing a part. Depending on the cross section of the layer, the recoater blade may snag on the part because they are only ever a few microns away from each other. This is generally due to the part lifting off the plate or not completely binding with the layer beneath it. The previously welded layer can curl due to the heat applied, thus providing the recoater blade a place to grab onto the part. This normally results in a machine jam but can sometimes end with the part being ripped off the platform.

Part Orientation

This is where part orientating becomes paramount in many ways. Orienting the part in the best possible way yields a result that reduces the chance of failure, build time, support application, support removal time, and machining time. It also creates an opportunity to protect the A-surface/features from needing any additional machining.

Ideally, the cross sections are similar in shape to circles or an open "U" shape. These shapes provide easy lead-ins for the recoater blade. Any rectangular surface that cannot be avoided

needs to be angled 5° off perpendicular to the blade to allow smooth contact. If possible, orientate the part in such a way that the thin parts are perfectly perpendicular to the blade, reducing the stresses put on the part. As an overall good practice the corners should be rounded with .5mm radii. The part should never be angled into/towards the recoater blade otherwise the blade will grab the nearest point and pull the part up into the blade.



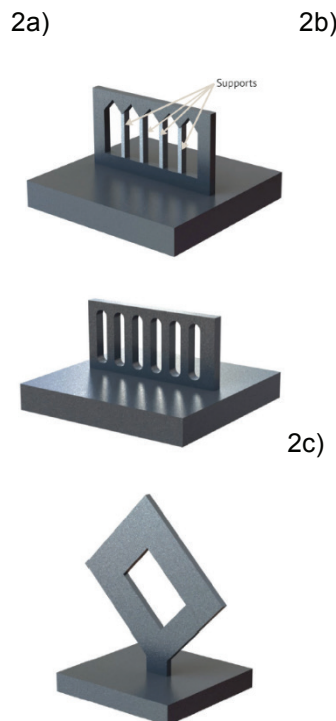
Figures 1a-e. Figure 1a shows the ideal cross section. 1b shows the worst case scenario cross section. 1c shows a part angled so that there is an easy lead-in spot. 1d shows how rounded edges provide lead-ins without needing to angle the part. 1e shows that a part should not be angled towards the recoater blade.

In terms of reducing support application, there are many different features that need to be

considered when looking at a component. Each printable material has a certain tolerance that it can reach before the material is no longer self-supporting. These are the angles using the XY-plane as reference:

Aluminum - 45°
Cobalt Chrome - 30°
Inconel - 45°
Stainless Steels - 30°
Titanium - 20-30°

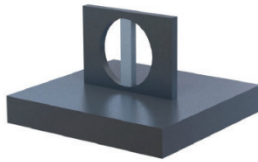
Any unsupported surface at a more acute angle than that will result in a failed build. Any surface that is just more obtuse than that will require a good amount of post processing due to laser shine through. The best course for orientating a part with many angles is to choose the orientation that leaves the most important surfaces untouched by supports or leaves the least amount of clean up. In the case where hollow parts are being built, one must orient the part so that no supports are necessary. If that cannot be done, then there are ways to remove the supports, but they should be kept to a minimum no matter the amount of supports needed on the outside surfaces. Hollow parts will also need to have an outlet somewhere to release the trapped powder inside the part. The hole can later be welded shut.



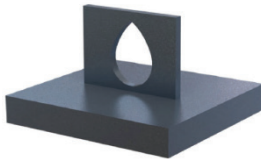
Figures 2a-c. Figure 2a shows how a downward facing surface was altered to self-supporting angles reducing need for support. 2b shows an alternative route to 2a, reducing the need for supports altogether by changing the design. 2c shows how part orientation can solve support reduction without changing the design.

Sometimes, parts will have internal channels or tubes that need to be built but cannot be done without supports. Generally, the best course of action is to change the channel geometry in order to eliminate supports.

3a)



3b)



Figures 3a-b. Figure 3a shows unaltered CAD data and necessary supports. Figure 3b shows the design has changed to create a shape that no longer needs support. This design thinking is incredibly helpful when creating inner channels in a part.

So, with the combination of orienting the part to provide easy lead-ins for the recoater and reducing surfaces that need supports, the result facilitates easier support removal. The more supports a part has the more it will need to be hand machined, when in the first place, one of the goals of 3D printing is to eliminate machining. One of these orientations can be more important to the customer depending on their needs. Say their need is time sensitive. Then the build can be adjusted so that the z-height is as minimal as possible to reduce build time. But, usually that means there are many supports that need to be removed, adding a lot of time to finishing the part. So, if one part orientation allows for minimal machining but costs more due to z-height in the build envelope, then they would choose that route to get it quicker. Usually one orientation can satisfy more than one of these needs.

Finally, the best way to reduce supports is to make design changes to the part itself. Could a 40° angled wall be changed to a 45° angled wall to eliminate necessary supports? Could the tube be changed to a teardrop shape? Can the downward facing surfaces be curved? Can the part be hollowed out to save build time & reduce internal heat stresses, yet still be as strong as the original?

4)

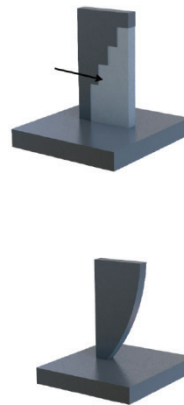


Figure 4. This shows how a design can be changed from a stair-stepped surface requiring supports to a smooth curve requiring no supports.

All these questions & more should constantly be held in mind when designing the part. In the end it's about whether the part accomplishes its purpose. If the part can do so with these design changes, then they should be done. Because it's not just about designing a usable piece, it's about designing for the 3D metal printing process.

Supports vs Anchors

Supports are used to hold the part or surface up in space. Anchors are used to hold the part secure to the build platform. The majority of the time support systems are made of block supports, an extruded grid network. Anchors are normally extruded rectangles or cones. These two features work in concert.

With good design practices, supports can and should be minimized. However, they perform quite a few vital functions in the process of

growing the part. First and foremost, they support the newly melted surface specifically on the shallow angles. Second, they prevent the geometry from warping and deforming. Finally, they act as heat sinks to dissipate heat away from the build. The heat accumulated during the build process is conducted away from thicker parts. Rather, the whole part could be made of relatively thin walls which reduce weight while allowing heat to escape from all areas of the component. Now, the walls will tend to fail once they get below a 1mm wall thickness. Yet, if supported, smaller wall thickness are achievable.

Anchors take the second purpose of supports and amplify that effect. They are solid features such as cones and cubes that can be added in by Boolean operations in support generation programs such as Magics3D. The solids are mated directly to the build platform so that the internal stresses of the parts can be alleviated by dispersing the stress through the larger mass of the platform.

It is hard to discern whether or not a part will need anchors. No matter the situation, the part will need to be attached to the build platform in order to build successfully. As a good measure, at least one anchor should be added if no surface of the part is directly attached to the plate.

IMPACT OF DIMENSIONAL ERRORS ON DESIGN OPTIMIZATION METHODOLOGIES

Build Parameters

Currently, all of our materials have been run by EOSINT M270, EOSINT M280, or SLM280 machines. If one were to make the same geometry out of every material, no build would be the exact same. This is due to almost entirely the support set up, since each material has different self-supporting angles. However, each material conducts heat differently, reacts to gases differently, and machines differently.

Titanium and aluminum for example must always be run in argon atmospheres. These two materials are the exception to all the other materials that we run in our machines. While the other materials are run at 20 & 40 microns levels, titanium runs at 30 microns and aluminum runs at 30 & 50 micron levels. The reason being for these parameters sets are the way the materials conduct heat.

Titanium builds up heat very quickly. So the build must be oriented in such a way that each

cross section covers as small a surface area as possible. Otherwise, the stresses accumulated during the build can cause the part to crack, warp off the plate, or even take the platform with it causing the build to halt. This is true for other materials too, yet titanium needs to be prepared more meticulously in this way. It would also make sense that titanium needs more supports to a) dissipate the heat away quicker and b) hold the part to the plate more securely. Aluminum also heats very quickly but since it is softer tends to warp much more than titanium. For this reason, supports and anchors are just as important to secure the part to the platform.

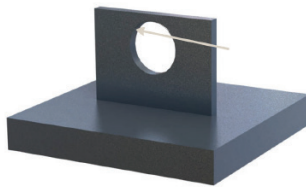
Adding Stock

Also, since aluminum is very easily machined, the tolerance for warp is very low. To counteract this, the shrink value can be accounted for by scaling the part. This operation is not always easily determined as it differs on a part to part basis. Until the part has been run once it is not possible to tell how much it will shrink. Therefore, even with this operation to counteract for warp or shrinkage, stock should be added to the part to allow for secondary machining to get it to CAD data. There are certain stock modifications for certain features that will make for a good finished part. When turning or milling surfaces .381-.762mm needs to be added. For reamed holes, .127mm per side is sufficient. Larger diameter holes/passages need .101-.203mm to remain as built. Finally, if any surfaces need to be polished, .050-.101mm will account for any material removed to keep it dimensionally correct. These operations may be performed on the same surface. Due to this, it is good practice to add more stock than total necessary to account for any foreseen errors.

Aluminum is not the only part that this may be needed for. Every other material we run can benefit from adding stock. For materials that are stronger, such as Stainless Steel, not as much may need to be added due to it coming out closer to CAD data off the machine.

Stock is useful in that it also will help eliminate the "stair-stepping effect." Because of the nature of the 3D metal printing process the parts will not have perfectly smooth surfaces. This is especially apparent on the shallow downward facing surfaces. Essentially, the topography of the geometry is showing a contour of where each layer was welded to the previous one. With

secondary machining this can be removed to achieve a smooth continuous surface.
5a)



5b)

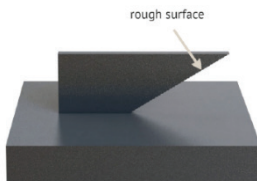


Figure 5a-b. Figure 5a shows where a rough stair step result would be on a shallow downward oriented surface. 5b shows that even though the surface isn't parallel to the platform there will be a stair-stepping effect revealing the contour lines.

Subtractive Features during the Build

When adding features such as threads, countersunk & counter bored holes, grooves, pockets & pads, keep in mind that machining may be necessary still.

Threads can be built successfully when oriented vertically. Any other direction is highly subject to failure. In general, it is best to build all cylindrical features vertically when possible. Orientation on any other axis will possibly result in oblong cross sections rendering the part unusable in some cases.

Countersunk & counter bored holes likewise can be built into the CAD data and printed on the machines. Yet, it is advised that they be tapped during post processing in order to ensure dimensional accuracy. Another feature such as grooves can also be successfully printed. If the groove has a 90° or acute angle profile then it can be built successfully requiring no need for support. Still, it is recommended in almost all cases that the grooves be milled or lathed post-build. This is especially true when the groove is cylindrical in nature, such as grooves for rubber O-rings.

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RELATION BETWEEN TIP SIZE, DEPOSITION SPEED AND ROUGHNESS IN FDM TECHNOLOGY.

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ABSTRACT

FDM technology builds parts using joint wires by layers with final roughness between 8 and 50 Ra (μm). The main characteristics which define this roughness are; the tip size and the angle of construction. Those characteristics, called “Stair Stepping Effect” are showed in Figure 1 [1].



Figure 1. “Stair Stepping Effect” in FDM technology.

On reference [1], the authors also show a prediction model related to the roughness based on the height of the layer and the angle of construction, Figure 2.

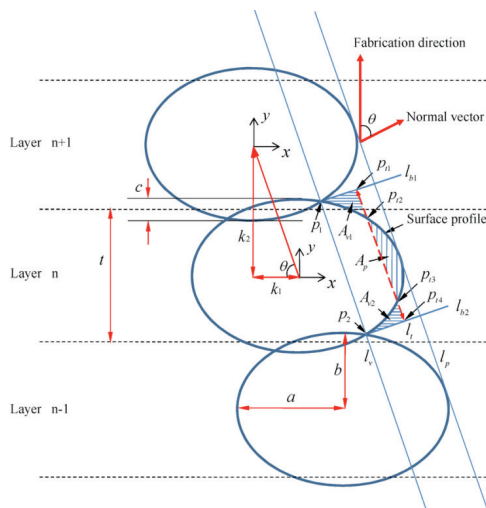


Figure 2. Representation for the surface profile modeling of the FDM-processed part [1].

Figure 3 illustrates the relation between two different tip sizes (height of layer) using this model.

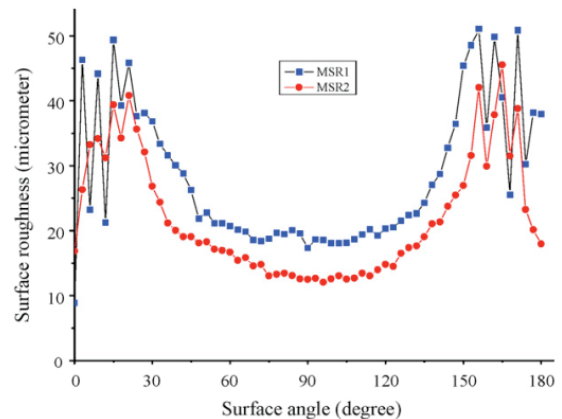


Figure 3. Measured roughness for T16 Tip (MSR1) and T12 tip (MSR2).

Based on these results, the aim of this work is to show the relation between the tip size, building speed, volumetric flow and roughness.

FDM PARAMETERS

FDM technology has different parameters that affect the final result of the manufacturing such as: the tip size, building material, support material, internal and external raster conditions, air gap, among others. In Table 1 it can be seen shows the relation between the slice height and the tip size.

TABLE 1. Relation between tip size and slice height.

Tip size	Slice Height (mm)
T10	0.1270
T12	0.1778
T16	0.2540
T20	0.3302

Some of the building style parameters for FDM are a consequence of the combination of the tip size and the building material (Figure 4 and Table 2).

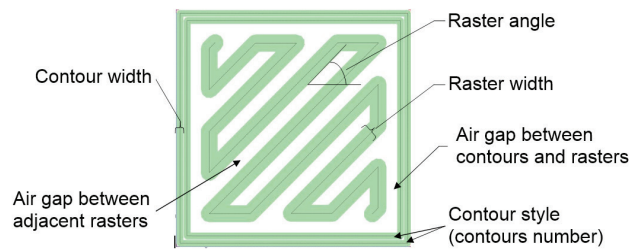


Figure 4. Building parameters defined as a consequence of the tip size and building material.

TABLE 2. Relation between the tip size and raster size [mm] for different building materials.

MATERIAL	T10	T12	T16	T20
ABS-M30				
ABSi	0.2032-	0.3048-	0.4064-	0.4572-
ABS-M30i	0.5782	0.7298	0.8314	0.9822
PC-ABS				
PC		0.254-	0.4064-	0.4572-
PC-ISO		0.679	0.8814	0.9822
ABS-ESD7		0.3048-	0.4064-	
		0.7298	0.8314	
Ultem 9085			0.4064-	
			0.7814	
PPSF/PPSU			0.4064-	0.4572-
			0.7814	0.9822

Due to the anisotropic effect of the technology and the “Stair Stepping Effect”, the combination of building material, the tip size, building parameters and orientation; results in different mechanical properties and surface finishing.

The results found in reference [2], suggest a tip size of T12, an angle orientation of 0° , a raster angle of 0° , a raster width of 0.456mm and, an air gap of 0.008mm to produce the best dimensional precision on a FDM construction.

These results combined with the graph of Figure 3 suggest the advantage of the tip size T12, but do not represent the effect of building speed.

BUILDING SPEED ANALISYS

In order to find the correlation between building speed and different tip sizes, our suggestion was to simulate the construction of two different

testing volumes using the Insight Software V 8.1. The size of the testing volumes were of $10 \times 10 \times 115.57 \text{ mm}^3$ and $400 \times 350 \times 115.57 \text{ mm}^3$. Both volumes has the same height, that is a multiple of an entire number of slices, no matter the tip size used. These volumes are shown in Figure 5, that shows the relation between the tip size, height and slices for the testing volumes.

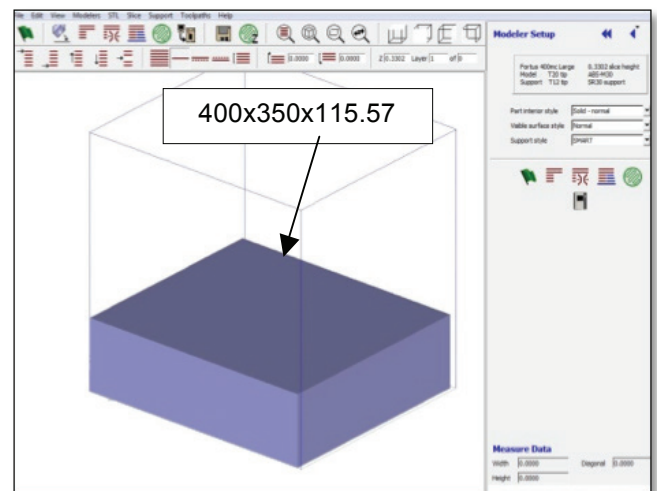
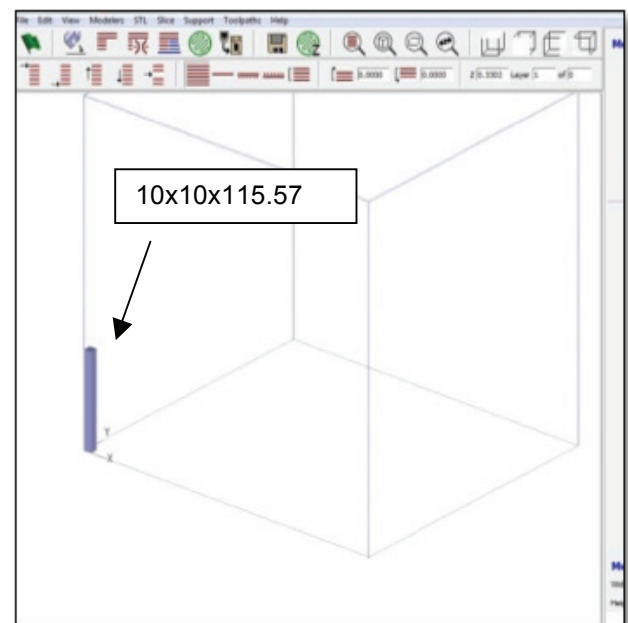


Figure 5. Graphical representation of the testing volumes.

TABLE 3. Relation between the tip size, height, and slices for testing volumes.

Tip size	Height (mm)	Slices
T10	0.1270	910
T12	0.1778	650
T16	0.2540	455
T20	0.3302	350

For these simulations, the building parameters used for every tip size (raster width, contour style, raster angle and air gap) were the same. These simulations were performed using ABSM30 as building material and a Stratasys Fortus 400 machine, using the same deposition area and a different deposition volume (as a result of the different height for every tip size employed). On Figure 6, a graphical representation of the relation between the deposition speed and the building area was shown, also the volumetric flow and the building area for different tip sizes are included.

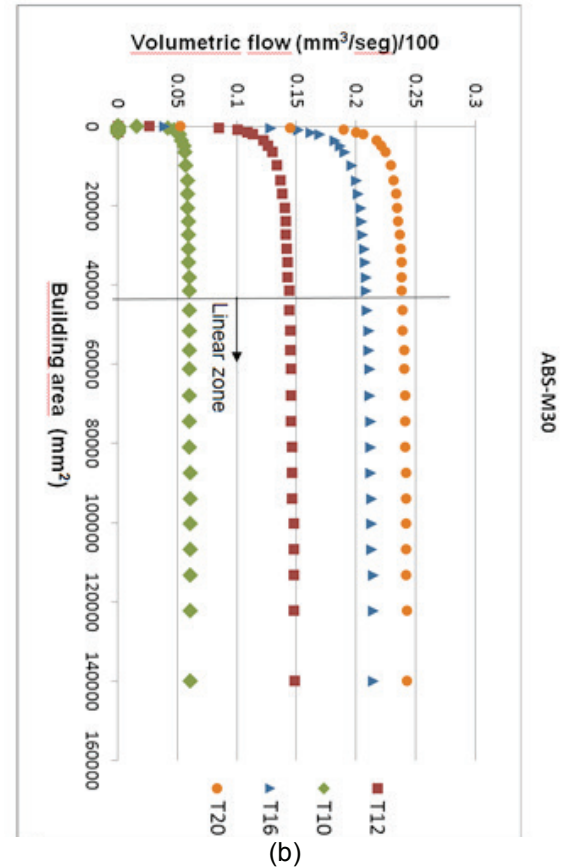
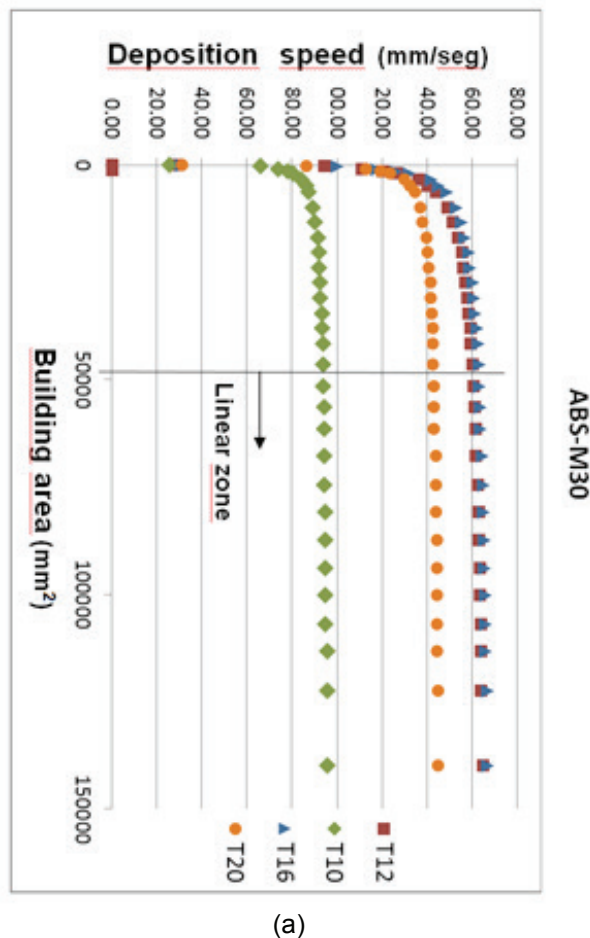


Figure 6. Graphical representation of the relation between (a) the deposition speed and the building area; (b) the volumetric flow and the building area for different tip sizes.

Applying the same simulation to different building materials; the results shown in the Table 4 and Figure 7, were found.

TABLE 4. Relation between the tip size and deposition speed, and between the tip size and volumetric flow, for different materials.

Material	Tip size	Deposition Speed (mm/s)	Volumetric Flow (mm ³ /s)
ABS-M30	T10	95.5	6.16
	T12	165.5	14.83
	T16	167	21.5
	T20	145	22.5
PC	T12	131	11.83
	T16	190.5	24.5
	T20	121	20.3
PC-ABS	T10	94.5	6.16
	T12	143	12.83
	T16	189.5	24.5
	T20	144.5	24.3

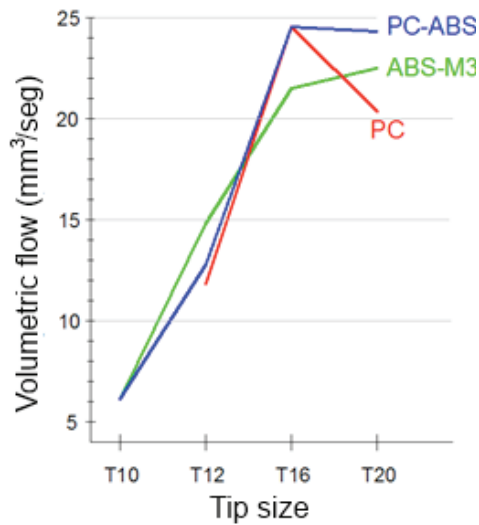


Figure 7. Graphical representation of the volumetric flow and tip size for different building materials.

RELATION BETWEEN BUILDING ANGLE AND TIP SIZE

The design of a geometric gauge (Figure 8) was proposed to find the angle error by means of the building orientation (vertical or horizontal). The geometric gauge has surfaces oriented in different angles with two different materials. The results of the measured process for this geometric gauge are showed in Table 5.

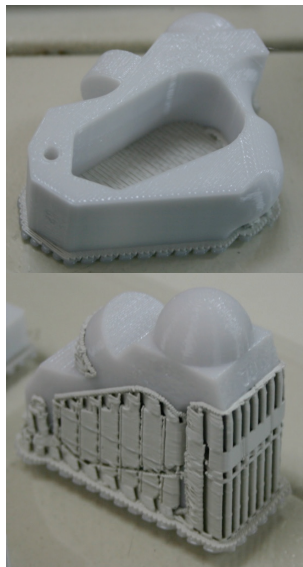


Figure 8. Built geometric gauge in two different orientations: horizontal (top) and vertical (bottom).

TABLE 5. Angle measured variation on two different orientations and two different materials

Nominal Value	Measured Values			
	PC-ABS		PC	
	Vertical	Horizontal	Vertical	Horizontal
10	10.35	10.00	9,80	10,10
20	20.10	20.00	19,85	19,95
25	25.30	25,10	25,35	25,05
30	30.00	30.00	29,80	29,90
40	40.50	40.00	40,50	40,05
50	50.15	49,65	49,75	49,90
60	59.75	60,05	59,65	60,15
70	69.60	69,85	69,70	70,10
80	79.65	79,75	79,60	80,15
90	90.45	90,10	90,30	90,05
Average Angle Variation	0.30	0.09	0.29	0.10

On Figure 9, the surface finishing for two different orientations (horizontal and vertical) are shown.

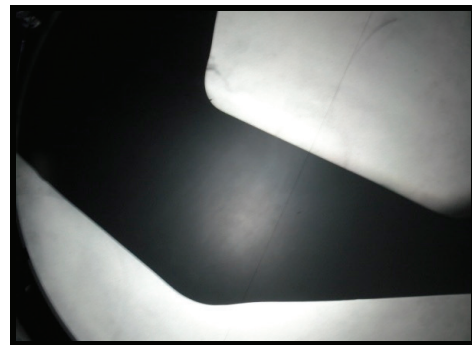


Figure 9. Surface finishing for two different orientations (a) horizontal and (b) vertical.

DISCUSSION

In this work, a simulation of the construction of two testing volumes with four different tip sizes

were done, to find the volumetric flow for three different materials (ABSM30, PC, and PC-ABS), using a Stratasys Fortus 400 machine. These actions result in the definition of a minimum stability area, and from this area minimum area value on, every material and tip have a linear behavior. With this information we were able to establish the combination of tip and material that offers the best deposition speed and could be able to correlate with the results shown in Figure 3, to establish a comparison between speed / tip size / building material and roughness; finding that the T16 tip size represents the best relation between speed deposition and roughness.

CONCLUSIONS

The tip size is one of the most important parameters related to roughness, but the orientation of building has a major impact on the same tip size. Also, both parameters, tip size and orientation, have a huge influence on the final precision, hence the designer and/or the operator must pay particular attention to these correlations in order to optimize the building time vs the roughness.

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Enhancing Surface Finish and Dimensional Accuracy in Additive Manufacturing Using Global Adaptive Direct Slicing

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INTRODUCTION

Additively manufactured (AM) parts are produced layer-by-layer from a Computer Aided Design (CAD) model. Traditionally, the CAD model is transferred to an AM system after exchanging to Stereo-lithography (STL). It is then sliced using different algorithms and machine constraints. Due to associated error and uncertainty with STL, it is preferable to directly slice the CAD model.

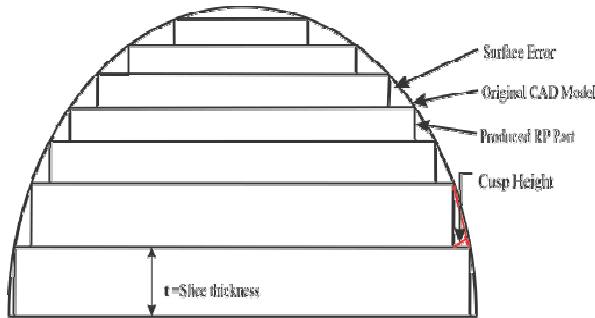


FIGURE 1: Cusp height and staircase effect

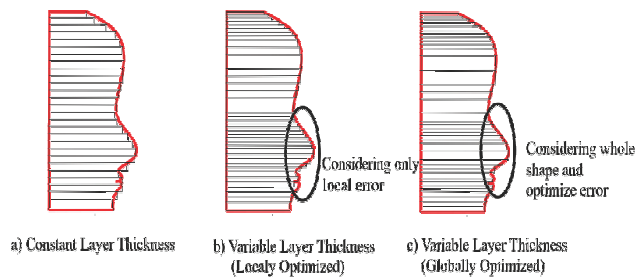


FIGURE 2: Different types of slicing and their effect on texture error.

The above figures 1 and 2 depict the staircase effect and differences between slicing with constant thickness, variable thickness (locally optimized) and variable thickness (globally optimized). This paper proposes a global direct adaptive slicing algorithm based on dimensional

accuracy and compares the results with constant layer thickness algorithms.

SLICING ALGORITHM

In the proposed algorithm, IGES standard format is used to transfer CAD models to the AM computational environment [1]. The developed algorithm receives an IGES form of CAD data as input and converts it into a customized database based on geometric features.

Dimensional Error Calculation

The dimensional error is computed using the λ numbers of points belonging to two consecutive layer surfaces. For each pair of points (P_i and P_{i-1}) in the consecutive slices, the dimensional area loss, e_p , is computed by integrating the profile curve $C(u)$ with the produced slice. The intersection points between the profile curve and the produced layer is computed first. Then profile curve is integrated between the intersection points u_1 and u_2 as shown in the following equation:

$$A_i = \int_{u_1}^{u_2} C(u) du \quad (1)$$

The profile area loss, e_p , for $P_i - P_{i-1}$ patch is calculated as follows, where μ is the number of intersection points between the profile curve and produced rapid prototyping surface (Figure 3).

$$e_p = \sum_{i=1}^{\mu-1} A_i^2 \quad (2)$$

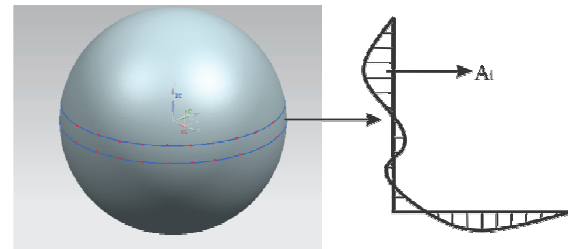


FIGURE 3: Dimensional Error Calculation

Dimensional area loss at i^{th} slice ϵ_i :

$$\varepsilon_i = \sum_{j=1}^{\lambda} e_j \quad (3)$$

Where e_j is the dimensional area loss of the individual j -th pair of points in two consecutive layers. The total dimensional area loss, E_t , for the entire CAD model is computed from the following equation:

$$E_t = \sum_{i=1}^{\kappa} \varepsilon_i \quad (4)$$

Where κ is the total number of slices. The Average Dimensional Area Loss (ADAL) ξ for the slice is calculated from the equation by considering the root mean square value.

$$\xi = \sqrt{\frac{\sum_{i=1}^{\kappa} \varepsilon_i}{\kappa}} \quad (5)$$

Optimization of Layer Thickness and Slice Number

A user inputs the desired number of layers. The slicing heights are then optimized by the genetic algorithm constrained by machine specifications. The objective function of the algorithm is to minimize the ADAL function ξ . The genetic algorithm starts with a population that consists of a randomly selected layer thickness based on the height of the CAD drawing. The genetic algorithm iterates to minimize the objective function. After the iterations, the genetic algorithm gives the slicing height matrix for and the minimized ADAL function value for a given number of layers.

CONCLUSION

Comparing the results of proposed implementation with the common practice for several case studies shows that the proposed approach has greater slicing efficiency and optimized dimensional error.

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Application Specific AM Technology Development for High-End Mechatronic Systems

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Abstract

Selective laser melting (SLM) is an additive manufacturing technique by which structural geometrical complex parts can be created directly by selectively melting consecutive layers of powder.

Although SLM is not a high-precision technology, it finds its application in specialized mechatronic equipment because it enables to re-think design and engineering. Performance gains can be achieved by making subassemblies smaller and lighter, through optimizing fluid dynamics or by reducing manufacturing cost.

Where additive manufacturing (AM) is often portrayed to offer freedom of design, it comes with its own set of limitations.

In regards to meet the requirements of mechatronic applications, process development in the field of dimensional accuracy, surface roughness and surface cleanliness is mandatory.

However, of prime importance are the process requirements which are at the core of the SLM process to enable AM material and component validation which ultimately enable its adoption as a volume production technology.

Functional Design

SLM is not a replacement technology for conventional metal working. Dedicated design to take advantage of AM's unique capabilities is the key to validating novel applications.

The basic design philosophy is to start from the functionality rather than from the manufacturability.

Although design optimization software is available, the best results come from an iterative approach in which functionality and manufacturing constraints are balanced. In this

stage, a close collaboration between the application engineer and the SLM engineer is instructional.

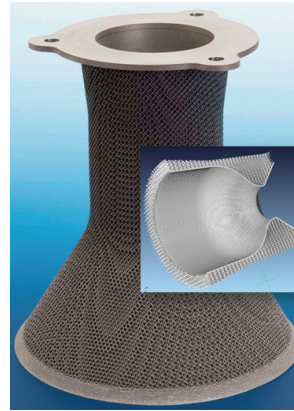


FIGURE 1. Lightweight structural component in Ti Grade 5 made by SLM technology.

Geometric Tolerances

Laser based metal AM is characterized by a topological resolution of $\pm 0.05\text{MM}$. Profile and place tolerances are subject to thermal stresses. This effect is directly affected by the in-layer dimension.

Novel applications demand for large scale SLM. At the same time, for cost reasons, there is an increase in build rates. Both the size and productivity requirement affect the SLM resolution.

The trend of the technology development of the LayerWise SLM apparatus is to increase build rates and part size while keeping the original resolution.

Surface Aspects and Cleanliness

SLM surfaces are characterized by a pearl-like roughness of approximately 5 Ra. While SLM materials can be processed at theoretic full density and can be mechanically polished, this is not possible in hidden cavities.

Dedicated surface improvements for layered components (SILC) are used. A special SILC

process enables ISO Class 0 cleanliness. As such AM can be applied in critical areas like microscopes or lithographic apparatus.

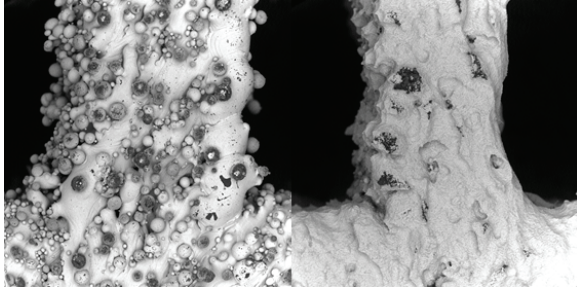


FIGURE 2. Surface cleanliness of AM materials

Component and material validation

AM Processes create both geometry AND material. This is an essential difference with conventional machining.

Although this may seem of only secondary importance, material validation is mandatory for long-term acceptance of AM. Dedicated quality controls as in-process monitoring are instructional to validate AM series.

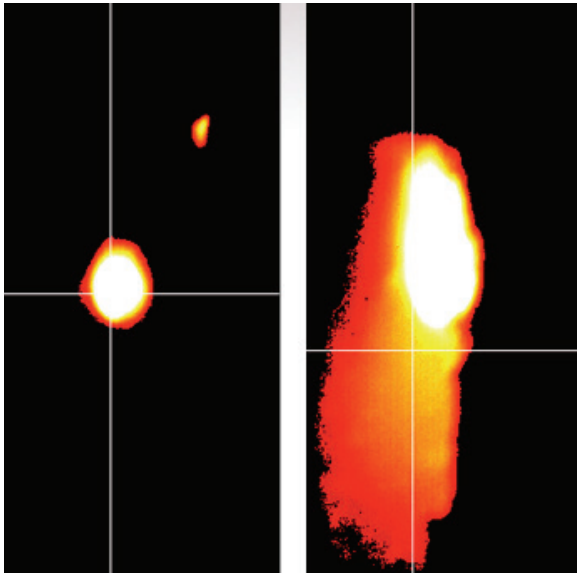


FIGURE 3. SLM Process monitoring, in casu the effect of oxygen content on melt pool behavior

Conclusion

SLM components can be used in high-end equipment to overcome complex engineering problems. Although AM is a young manufacturing technology, manufacturing principles and technologies are developed to

enable consistent part quality, to enable new applications and to facilitate high-volume manufacturing.

Using Acetone Vapour Treatment to Improve Secondary Finishing Operations in Additive Manufacturing

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INTRODUCTION

Additive Manufacturing (AM) is necessary when the complexity of a desired part is relatively high and conventional manufacturing processes will not suffice. In AM, parts are produced in a layer-by-layer form from a Computer Aided Design (CAD) model. The current practice in industry is to exchange the data from CAD to Stereolithography (STL) format [1]. STL is a triangulated tessellation and offers simplified data for faster computational slicing. One of the issues with AM is the associated error caused by the staircase effect as seen in Figure 1.

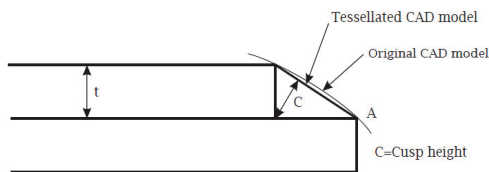


FIGURE 1. Staircase effect [2].

The staircase effect has driven the necessity of secondary finishing operations with a goal of improving surface finish and aesthetic appearance. This paper will discuss current industry practices, and propose an optimized development of a relatively new method: vapour treating AM parts with acetone.

CURRENT INDUSTRY PRACTICES

Methods of secondary finishing for additive manufacturing can vary depending on the desired purpose of the part. An example of a more complex AM use is tooling for vacuum-assisted resin transfer moulding. If this is desired, multi-stage and complex finishing is required using resin infusion, sanding, priming, painting and waxing [3].

A more common purpose for post processing in AM is to remove the staircase effect while maintaining geometrical accuracy and improving surface finish. Some of the current industry practices for post processing are [4]:

- Dipping in acetone
- Vapour treating with acetone
- Sanding
- Coating with epoxy resin



FIGURE 2. Vapour treating with Acetone [5].

Acetone vapour treatment is a relatively new idea in post processing for additive manufacturing. Its application is primarily with ABS as this thermoplastic material dissolves on contact. Vapour treatment is done by putting a small amount of Acetone in a large container on a heating device. It is heated at 120° C until the acetone begins to vaporize. Once the vapour has surrounded the volume of the container the temperature is dropped to 90° C to hold it in vapour form [4]. This process can be seen in figure 3.

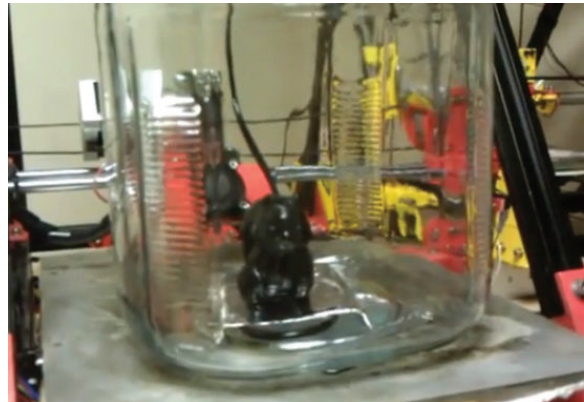


FIGURE 3. Acetone Vapour Treatment [5].

OPTIMIZATION OF VAPOUR TREATMENT

A series of experiments are conducted varying exposure time and steady state vapour temperature on multiple copies of the same AM part individually with various surface roughness specifications. For each part the exposure time are logged. Then surface finish is studied using 3D surface topography device and dimensional accuracy will be measured with a Coordinate Metrology Machine. Experimental correlation between the vapour treatment parameters and the Surface roughness reduction are developed. The experimental correlation is validated using various case studies with complex geometries.

CONCLUSION

Exposure time and temperature are studied against surface finish, and then separately against dimensional accuracy. Using the quantitative data a mathematical model is developed that can be used directly for post processing of AM parts with arbitrary shapes and geometries.

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Authors Index

Adam, Guido A.O. 30
 Alexander, Paul 71, 86
 Anam, Md. 37
 Anderson, Andrew T. 7
 Badami, Vivek G. 135
 Barari Peng, Ahmad. 43, 145, 219, 223
 Bauza, Marcin B. 86
 Bayley, Cindy. 98
 Beaman, Joseph J. 70
 Beaucamp, Anthony Tadeus 62
 Bechmann, Florian 109
 Bediz, Bekir 167
 Bergmann, André 19, 201
 Bhogaraju, Raghuram 86
 Bochmann, Lennart. 98
 Boucher, Christopher 131
 Bourell, David L. 70
 Brenne, Florian 36
 Brown, Christopher A. 157
 Brown, William D. 71
 Buls, Sam 109
 Burke, Stephen 71, 86
 Caballero-Ruiz, Alberto 214
 Charlton, Phillip 62
 Christison, Mark S. 173
 Ciftci, Meltem 24
 Clijsters, Stijn 109
 Colonna de Lega, Xavier 135
 Corbett, Taylor. 186
 Coward, Andrew 80
 Craeghs, Tom 109
 De Bruyne, Tom. 221
 Deiss, Olga 13
 Dickman, Corey. 184
 Dilip, Samuel 37
 Dillingh, Bert 205
 Dinardo, Joe 131
 Divin, Charles J. 71, 177
 Donmez, M. Alkan. 123
 Dornfeld Ph.D., David A. 98
 Drescher, Joseph D. 123
 Ebert, Marie-Christin. 109
 Elsbrock, Sam 209
 Fay, Martin Freestone 135

Ferencz, Robert M. 7
 Fish, Scott 70
 Gerd, Witt 13
 Giusca, Claudiu 127
 Gong, Haijun 37
 Goudsmit, Frans-Willem 51
 Graziano, Arthur A. 62
 Grimm, Tobias 139
 Gu, Hengfeng 37
 Hansen, Hans Norgaard 104, 179
 Hao, Bohan 167
 Hayes, Greg R. 205
 Hein, Christoph 201
 Helu, Moneer 98
 Hocken, Robert J. 92
 Hodge, Neil E. 7
 Hoppenbrouwers, Mark 205
 Hurlbut, Colin 98
 Jamiolahmadi, Saeed 43
 Jamshidinia, Mahdi 45
 Jared, Bradley H. 131
 Jeon, Yongho. 147
 John, Patrick 19
 Jones, Griffin. 80, 184
 Jones, Nick H. 56
 Joshi, Sanjay 80, 184
 Kaji, Farzaneh 223
 Kamath, Chandrika 7
 Kashevko, Vasyl. 19
 Kempen, Karolien 76
 Khairallah, Saad A. 7
 Kim, Ga Eun. 147
 King, Wayne E. 7
 Kishawy, Hossam 219, 223
 Knebel, Richard 86
 Kok, Thijs. 186
 Korkmaz, Emrullah 167
 Kovacevic, Radovan 45
 Kruth, Jean-Pierre 76, 109
 Kurfess, Thomas R. 4
 Land, William Stafford. 151
 Langelaar, Mathijs 9
 Leach, Richard K. 127
 Lee, ChaBum. 186

Lee, Dong-Mok	196
Lee, Hoon-Hee	196
Lee, Moon-Gu	147
Leigh, David K.	70
Lell, Friedemann	
Leuders, Stefan	36
Liou, Frank	114
Liu, Heng	114
Macaulay, Gavin	127
Martz Jr., Harry E.	71, 86, 177
Meinert, Kenneth	184
Mello, Brad C.	157
Milne, Katherine	127
Miyakawa, Kodai	163
Mönzer, Jan	13
Morse, Edward P.	92
Moylan, Shawn P.	11, 82, 86, 123
Müller, M.	30
Murray, John D.	66
Namba, Yoshiharu Y	62
Nassar, Abdallah	184
Nielsen, Jakob Skov	104
Niendorf, Thomas	36
Oberschmidt, Dirk	201
O'Connell, Mark T.	86
Oosterhuis, Gerrit	24, 51
Ortega-Rodríguez, Adolfo	214
Ott, Michael	13
Ozdoganlar, Osman Burak	167
Pal, Deepankar	37
Palmer, Todd	184
Panas, Robert Matthew	71, 86
Patil, Nachiket	37
Pawlikowski, Gregory T.	67
Pedersen, David Bue	104, 179
Peijnenburg, Antonius T.	51
Qian, Jun	76
Rasmussen, Jakob	104
Rathbun, Howard	71
Reinarz, Bernd	13
Rengers, Steve	3, 108
Reschetnik, Wadim	190
Reutzel, Edward	80, 184
Riahi, Golara	24
Richard, Hans Albert	36, 190
Riemer, Andre	36, 190
Roblee Ph.D, Jeffrey W.	119

Ruiz-Huerta, Leopoldo	214
Sain, John D.	177
Saint John, David B.	80, 184
Saiz, David	131
Schutten, Gerrit Jan M.	24
Sehrt, Jan T.	13
Sikder, Snahungshu	219, 223
Simpson, Timothy	80, 184
Slotwinski, John A.	11, 82
Sluiter, Erwin	51
Smith, Jerel A.	71
Smith, Stuart T.	92, 186
Smokovitz, Josh D.	86
Sparks, Todd E.	114
Stucker, Brent	37
Tahara, Hiroyuki	163
Takahashi, Satoru	163
Takamasu, Kiyoshi	163
Tarbutton, Joshua	186
Taylor, John S.	4, 71, 86
Thijs, Lore	221
Thole, Karen	80
Tran, Hy D.	131
Transchel, Robert	98
Triantaphyllou, Andrew	127
Trost, Hans-Jochen	173
Tröster, Thomas	36
Uhlmann, Eckart	19, 201
van Baars, Gregor	9, 205
Van der Perre, Wilfried	221
van Kampen, Jaap	13
van Keulen, Fred	9
Van Vaerenbergh, Jonas	221
Villarraga-Gómez, Herminso	92, 186
Villegas, Alejandro	24
Vogels, John	24
Wang, Jason	157
Wang, Kaixi	157
Welkenhuyzen, Frank	76
Westerwoudt, Victor	205
Wiora, Georg	139
Witt, Gerd	139
Yang, Seung-Han	196
Zeng, Yuqi	157
Zimmer, Detmar	30

Volume 57

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